

Unified Electromagnetic Theory of Matter and Light

Section B — Structure of Light

Part IV - Physical Structure of the Electromagnetic Wave

Franc Rozman

Abstract

This paper introduces a conceptual three-dimensional model of an electromagnetic wave as a continuous, periodically evolving physical structure. The model considers an approximately annular organization of the electric and magnetic fields and examines their transformation through an intermediate electromagnetic configuration associated with Maxwell's displacement current.

The electric field E , magnetic field B , and displacement current J_D are treated as coupled aspects of one evolving electromagnetic structure. The intermediate configuration is proposed to maintain continuity between successive phases of the wave and to participate in the redistribution of electromagnetic energy along the direction of propagation.

The model also examines the possibility that differences between the transverse distributions of the electric and magnetic fields produce a radial component of electromagnetic energy transport. This provides a conceptual basis for contraction of undersaturated waves, expansion of oversaturated waves, and the emergence of a dynamically regulated transverse structure characterized by approximately stable field amplitudes.

The present paper does not attempt to complete the quantitative development of this structure. Its principal purpose is to establish the geometrical, energetic, and dynamical framework of the electromagnetic-wave model.

Part V develops the subsequent evolution of the wave structure, including saturation, energy-dependent transverse size, coherent merging, growth of the characteristic transverse radius R_0 , and changes of wave energy during propagation. Part VI examines the local interaction of the electromagnetic wave with bound electrons and applies the model to the photoelectric effect, providing quantitative constraints on the characteristic field amplitudes and local interaction geometry.

Part IV therefore serves as the conceptual foundation for the later structural and interaction-based development of the model. Its remaining fundamental open problem is the construction of a complete three-dimensional electromagnetic field solution that reproduces the proposed geometry, energy transport, and transverse stability within the full Maxwell and momentum-balance framework.

1. Introduction

Part I describes electromagnetic tori, in which the electric and magnetic fields oscillate with a phase shift of $\pi/2$. In Part IV, attention turns to electromagnetic waves, where the electric and magnetic fields oscillate synchronously and propagate as a continuous structure.

Electromagnetic waves are conventionally described by Maxwell's equations, which determine the relationships between electric and magnetic fields and their propagation through space. The familiar sinusoidal representation describes the variation of these fields with position and time. It does not, however, by itself specify the complete three-dimensional organization of a spatially localized electromagnetic wave.

The present paper investigates the possibility that an electromagnetic wave possesses a continuous internal structure characterized by a transverse distribution of electric and magnetic fields. The proposed model considers an approximately annular field configuration whose internal geometry evolves periodically during propagation. Its longitudinal periodicity is determined by the wavelength λ , while its transverse organization is described by characteristic geometrical dimensions.

The electromagnetic wave is treated as one continuous structure rather than as a sequence of independent electromagnetic objects. Successive half-wavelength regions represent different phases of the same evolving electromagnetic process. This distinction is important because electromagnetic energy and transverse organization must remain continuous as the field configuration changes during propagation.

A central role in the proposed description is assigned to Maxwell's displacement current,

$$J_D = \epsilon_0 \frac{\partial E}{\partial t}.$$

For a sinusoidally varying electric field, the displacement current is shifted by one quarter

of a period relative to the electric field. The model examines whether this relationship can support a periodic transformation between the approximately annular field configuration and an intermediate electromagnetic configuration associated with displacement current and its accompanying magnetic field.

The intermediate configuration is proposed to maintain electromagnetic continuity between successive phases of the wave. Its contribution is not treated as an additional form of energy independent of the electric and magnetic fields. Rather, it represents a complementary electromagnetic configuration through which energy may be redistributed while the complete electromagnetic energy remains conserved.

The model also examines the possibility that the transverse dimensions of the electromagnetic wave are dynamically regulated. Small differences between the spatial distributions of the electric and magnetic fields may influence the radial component of the Poynting vector. An undersaturated configuration may consequently exhibit a tendency toward transverse contraction, whereas an oversaturated configuration may expand.

A dynamically regulated state is characterized by hypothetical saturated field amplitudes E_0 and B_0 . Electromagnetic waves containing different total energies may maintain approximately the same characteristic field amplitudes while possessing different transverse dimensions.

The present paper is intended primarily as the conceptual foundation of this electromagnetic-wave model. It develops the proposed three-dimensional geometry, electromagnetic continuity, periodic transformation through the displacement-current configuration, energy redistribution, and the basic idea of transverse regulation.

The subsequent parts develop these questions further. Part V examines the structural

evolution of the electromagnetic wave after this conceptual framework has been established. It considers saturation, energy-dependent transverse size, coherent merging of electromagnetic waves, growth of the characteristic transverse radius R_0 , redistribution of energy, and changes of wave energy and geometry during propagation.

Part VI then examines the local interaction of the electromagnetic wave with bound electrons. In particular, it applies the model to the photoelectric effect and uses the electron-ejection process to constrain characteristic field amplitudes, local interaction dimensions, and the relationship between total wave energy and locally transferred energy.

The purpose of Part IV is therefore not to determine all characteristic parameters independently. Its role is to establish the physical picture within which the later quantitative and interaction-based developments can be formulated.

The proposed interpretation does not modify Maxwell's equations. Rather, it investigates whether a continuous, spatially organized electromagnetic wave can be described through their coupled field dynamics together with the proposed transverse structural mechanism. Some questions introduced here are developed in Parts V and VI, while a more fundamental problem remains open: the construction of a complete three-dimensional electromagnetic field solution that reproduces the proposed geometry, energy transport, and transverse stability within the full Maxwell and electromagnetic momentum-balance framework.

2. Three-Dimensional Structure of the Electromagnetic Wave

Maxwell's equations describe the spatial and temporal relationships between electric and magnetic fields. They determine how electromagnetic disturbances propagate, but they do not prescribe a unique transverse geometry for every possible field configuration. The present model therefore investigates whether an electromagnetic wave can possess a continuous, approximately annular internal structure.

The proposed structure is characterized by three geometrical quantities: the wavelength λ which determines the longitudinal periodicity; the characteristic transverse radius R ; and the radial thickness a , which describes the region of concentrated electromagnetic energy.

These quantities represent different properties of the wave. In particular, the model does not assume that the transverse radius is proportional to the wavelength.

2.1. Annular Organization of the Electric and Magnetic Fields

The proposed electromagnetic wave contains a continuous region of concentrated electric and magnetic fields surrounding its propagation axis.

The electric field is assumed to possess a predominantly radial organization within this region, while the magnetic field follows an approximately closed transverse configuration. Their spatial distributions are coupled through Maxwell's equations and evolve continuously during propagation.

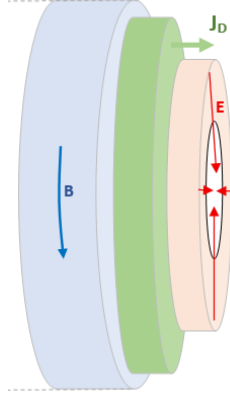


Figure 1. Schematic representation of the proposed transverse electromagnetic structure. The magnetic field B is concentrated predominantly in the peripheral region, while the electric field E occupies the inner region. The intermediate configuration associated with displacement current J_D is indicated schematically. The drawing illustrates the assumed spatial organization of the fields rather than a calculated Maxwellian field solution. The boundaries represent characteristic field regions, not material surfaces.

The absence of magnetic monopoles requires

$$\nabla \cdot B = 0$$

This condition is compatible with closed magnetic-field configurations, although it does not uniquely require an annular or toroidal geometry.

The model adopts such a configuration as a possible spatial organization of the electromagnetic field. Its physical validity must ultimately be established through a complete field solution.

The electric and magnetic fields are not assumed to occupy precisely identical radial distributions. Their characteristic positions, widths, and gradients may differ slightly. These differences are important because they may affect the direction of electromagnetic energy

transport and the transverse evolution of the wave.

The detailed field profiles remain to be determined.

2.2. Longitudinal and Transverse Dimensions

The wave propagates along its longitudinal axis, denoted by z .

Its periodicity is characterized by the wavelength λ . Within this continuous structure, successive regions of length $\lambda/2$ correspond to successive electromagnetic half-periods.

The characteristic transverse radius R describes the position of the concentrated annular field region. Its radial thickness is denoted by a .

The two transverse parameters should not be confused:

- R specifies the characteristic distance of the annular structure from the propagation axis.
- a describes the radial width over which its electromagnetic energy is concentrated.

Because electromagnetic fields have continuous spatial distributions, neither parameter represents a rigid material boundary.

For a relatively narrow annular region, an approximate effective volume over one full wavelength may be written as

$$V_{\text{eff}} \approx 2\pi R a \lambda$$

This geometrical expression provides a useful estimate but does not replace integration over the actual electromagnetic energy-density profile.

The longitudinal and transverse scales are therefore treated as distinct characteristics of the proposed wave structure. The wavelength determines the spatial period of oscillation, while the transverse dimensions describe the

organization of electromagnetic energy around the propagation axis.

2.3. Continuous Structure Along the Propagation Axis

The proposed electromagnetic wave is not regarded as a succession of independent toroidal objects.

Instead, its internal configuration changes continuously along the direction of propagation. Successive half-wavelength regions represent different phases of one connected electromagnetic process.

This distinction is particularly important at transitions between adjacent half-periods.

A reduction in the electric or magnetic contribution associated with one geometrical configuration does not necessarily imply a disappearance of the complete electromagnetic structure. The model proposes that energy is periodically redistributed into an intermediate configuration associated with displacement current.

Consequently, the transverse organization of the wave need not be reconstructed independently at the beginning of each half-period.

The proposed intermediate configuration and its role in maintaining energy continuity are examined in Sections 4–6.

2.4. Electromagnetic Energy Transport

The direction and magnitude of electromagnetic energy transport are described by the Poynting vector,

$$\mathbf{S} = \frac{\mathbf{E} \times \mathbf{B}}{\mu_0}$$

For the proposed wave structure, the dominant component of the energy flux is directed along the propagation axis.

The model also considers the possibility of a smaller radial component arising from the three-dimensional organization of the fields.

In cylindrical coordinates, the energy flux can be represented schematically as

$$\mathbf{S} = S_z \mathbf{e}_z + S_R \mathbf{e}_R$$

where S_z describes longitudinal energy transport and S_R describes radial energy redistribution.

A nonzero radial component does not necessarily imply that the complete electromagnetic wave changes its direction of propagation. In an approximately axisymmetric configuration, radial contributions on opposite sides of the propagation axis may cancel in the total transverse momentum while still participating in local energy redistribution.

The model proposes that changes in the relative spatial distributions of the electric and magnetic fields can influence this radial component.

At this stage, neither its magnitude nor its direction is derived from an explicit field solution. Its possible role in regulating the transverse dimensions of the wave is examined in Section 3.

2.5. Electromagnetic Energy and Field Geometry

The electromagnetic energy density in vacuum is given by

$$u_{\text{EM}} = \frac{\epsilon_0 E^2}{2} + \frac{B^2}{2\mu_0}$$

The total energy within a selected region of the electromagnetic wave is obtained by integrating this density over the corresponding volume.

For a spatially localized field configuration, the result depends on both the field amplitudes and their three-dimensional distributions.

Consequently, two waves with comparable characteristic electric and magnetic amplitudes

may contain different amounts of energy if their transverse dimensions differ.

This observation becomes important when considering the proposed saturated state. The model allows for the possibility that electromagnetic waves with different energies possess different transverse radii while maintaining approximately equal characteristic saturated amplitudes.

However, the existence of such a family of dynamically stable configurations is not established by the energy equation alone.

It requires a mechanism capable of maintaining the corresponding transverse field organization.

2.6. Geometrical Interpretation and Its Limits

The annular representation offers a possible three-dimensional interpretation of the internal organization of an electromagnetic wave. It provides a geometrical framework for examining energy transport, displacement-current dynamics, and the possible regulation of transverse dimensions.

It does not, however, follow uniquely from Maxwell's equations.

A complete physical description must establish electric and magnetic field distributions that satisfy the full Maxwell equations, conserve electromagnetic energy and momentum, and reproduce the proposed continuous propagation.

The present chapter therefore defines the geometrical framework of the model. The following chapter examines the hypothetical mechanism through which the transverse structure might become dynamically regulated.

3. Dynamic Equilibrium and Transverse Geometry

The proposed electromagnetic wave possesses a continuous transverse field structure characterized by a radius R and an effective radial thickness a . For this structure to persist during propagation, its electromagnetic energy and momentum must evolve in a manner consistent with the maintenance of its transverse organization.

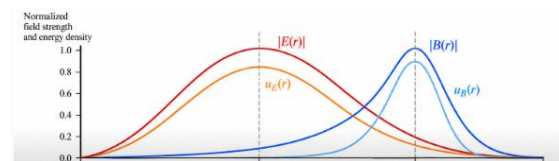


Figure 2. Illustrative radial distributions of the electric and magnetic fields and their corresponding energy densities. The electric-field magnitude is distributed over a broader inner region, whereas the magnetic-field magnitude is concentrated closer to the peripheral region. The differences between these distributions provide a possible geometrical basis for the proposed radial redistribution of electromagnetic energy. The curves are schematic and do not represent quantitatively calculated field profiles.

Maxwell's equations describe the coupling between the electric and magnetic fields, but they do not independently select a unique transverse radius or field amplitude. The present model therefore investigates a possible dynamical mechanism through which the spatial organization of the fields may regulate the transverse dimensions of the wave.

The central hypothesis is that small differences between the spatial distributions of the electric and magnetic fields influence the radial component of electromagnetic energy transport. As the field amplitudes change, these distributions may evolve asymmetrically, modifying the radial direction of the Poynting vector.

This mechanism is proposed to provide a tendency toward contraction in an undersaturated wave and expansion in an oversaturated wave.

3.1. Radial Organization of the Fields

The electric and magnetic fields are assumed to occupy approximately annular regions surrounding the propagation axis.

Their spatial distributions need not be identical. The characteristic positions and radial widths of their energy-density profiles may differ slightly.

Such differences are assumed to exist even when the electromagnetic wave is weak.

As a result, the combined field geometry may produce a small radial component of electromagnetic energy transport.

Taking the outward radial direction as positive, the model proposes that an undersaturated configuration exhibits

$$S_R < 0$$

The energy flux is therefore directed slightly toward the propagation axis while maintaining its dominant longitudinal component.

The electromagnetic wave continues to propagate forward, but its internal energy and momentum distributions may undergo transverse reorganization.

The resulting change in geometry must ultimately be determined by the electromagnetic momentum balance. The inward direction of energy transport is a proposed part of the contraction mechanism, not by itself a complete calculation of the radial force.

3.2. Contraction of an Undersaturated Wave

Consider an electromagnetic wave with a transverse radius larger than the radius corresponding to its saturated state at the same energy.

Its characteristic electric and magnetic amplitudes are consequently below their proposed saturated values.

Within the model, the small inward component of energy transport produces a tendency toward contraction.

If the energy contained in the selected wave region remains approximately constant during this initial response, reducing the transverse dimensions increases the electromagnetic energy density.

For a family of geometrically similar field profiles, the energy can be approximated by

$$W = C\lambda\epsilon_0 E^2 R^2$$

where C is a dimensionless geometrical coefficient incorporating the effective radial width and longitudinal field distribution.

This relation assumes a comparable electric and magnetic energy contribution and a nearly constant relative profile width. It is therefore an approximation rather than a general expression for an arbitrary field geometry.

At constant energy and wavelength, it gives

$$E \propto \frac{1}{R}$$

For corresponding field components satisfying the approximate relation $E = cB$, the characteristic magnetic amplitude increases together with the electric amplitude.

Thus, the proposed contraction mechanism provides a possible route by which a weak electromagnetic wave approaches a characteristic saturated field state.

3.3. Saturation and Radial Equilibrium

The model introduces hypothetical characteristic amplitudes E_0 and B_0 .

They describe a proposed saturated electromagnetic configuration in which the spatial distributions of the fields produce no net tendency toward further transverse contraction or expansion.

The defining amplitude condition is

$$E = E_0$$

with a corresponding characteristic magnetic amplitude B_0 .

At saturation, the model hypothesizes that the radial component of the Poynting vector associated with transverse energy redistribution approaches zero.

The energy flux is then predominantly longitudinal, and the transverse dimensions remain approximately constant during steady propagation.

This condition should be distinguished from the complete electromagnetic stress balance. A vanishing radial energy flux does not by itself imply a vanishing radial stress. The proposed equilibrium must ultimately satisfy the momentum balance of the complete field configuration.

The values of the saturated amplitudes have not yet been derived. Their existence and possible common value across electromagnetic waves of different energies remain hypotheses of the model.

3.4. Response to Oversaturation

Suppose a saturated electromagnetic wave receives additional energy while its transverse dimensions initially remain unchanged.

Its electromagnetic energy density increases, and the field amplitudes temporarily exceed their characteristic saturated values.

The model proposes that this oversaturation modifies the relative spatial distributions of the electric and magnetic fields.

Their resulting asymmetry may reverse the radial component of energy transport, giving

$$S_R > 0$$

The energy flux is now directed slightly outward.

If the corresponding electromagnetic momentum balance produces an expansive response, the effective transverse radius increases.

This expansion distributes the additional energy over a larger region and reduces the characteristic field amplitudes toward their saturated values.

The proposed mechanism therefore distinguishes three possible radial responses:

Field state	Radial energy transport	Proposed geometrical response
Undersaturated	Slightly inward	Contraction
Saturated	Predominantly longitudinal	Constant transverse dimensions
Oversaturated	Slightly outward	Expansion

The change in radial energy transport is attributed to the evolving three-dimensional field geometry. Its precise dependence on the field amplitudes remains to be determined.

3.5. Energy-Dependent Equilibrium Radius

An important consequence of the proposed mechanism is that saturation need not select a universal transverse radius.

If the characteristic saturated amplitude remains approximately constant, electromagnetic waves with different energies may possess different equilibrium radii.

Within the approximate geometrical model, the energy of a saturated wave region is

$$W = C\lambda\epsilon_0 E_0^2 R_{eq}^2$$

Consequently, at a fixed wavelength and for comparable field profiles, the equilibrium radius scales with the square root of the energy:

$$R_{\text{eq}} \propto \sqrt{W}$$

A wave containing more energy may therefore possess a larger transverse structure without requiring a larger saturated field amplitude.

This differs from a model in which all electromagnetic waves are assumed to converge toward one universal transverse radius.

The proposed saturation mechanism instead allows a family of possible equilibrium geometries characterized by their energies.

The relation does not, however, demonstrate that every member of this family is dynamically stable. Stability requires a restoring response to small deviations from the corresponding equilibrium radius.

3.6. Stability Against Small Perturbations

A dynamically stable configuration must respond to small transverse disturbances in a manner that tends to restore its equilibrium state.

Consider a saturated electromagnetic wave with energy W and equilibrium radius R_{eq} .

If its radius increases slightly while its energy remains approximately constant, the characteristic field amplitudes decrease below their saturated values.

The model predicts an inward radial response that tends to reduce the radius.

Conversely, a small decrease in radius increases the field amplitudes above their saturated values. The resulting oversaturated configuration is proposed to produce an outward radial response.

The corresponding restoring condition may be expressed schematically through a net radial effect F_r :

$$F_R(R_{\text{eq}}) = 0$$

For a stable equilibrium, a small displacement must produce a restoring tendency:

$$\left. \frac{\partial F_R}{\partial R} \right|_{R_{\text{eq}}} < 0$$

Here, F_r represents an effective radial contribution obtained from the complete electromagnetic momentum balance. It should not be interpreted as a separately established force acting on a rigid material boundary.

The proposed response to undersaturation and oversaturation is consistent with this stability criterion, but its quantitative verification requires explicit electric and magnetic field distributions and the corresponding Maxwell stress tensor.

3.7. Magnetic Closure and Transverse Organization

The proposed annular magnetic configuration introduces another possible contribution to transverse stability.

Since magnetic field lines have no isolated beginning or end, a closed transverse magnetic organization is geometrically compatible with Maxwell's equations.

A dynamically persistent closed configuration may also require an appropriate relationship between its spatial organization and the phase of the electromagnetic oscillation.

Such a condition could constrain the possible transverse dimensions or the radial distribution of the magnetic field.

However, magnetic closure alone does not establish a unique equilibrium radius. Nor has a quantitative phase-closure condition for the proposed propagating structure been derived.

These considerations remain possible supplementary constraints on the transverse organization of the electromagnetic wave.

They do not replace the proposed saturation mechanism or the requirement for a complete electromagnetic momentum balance.

3.8. Dynamic Equilibrium as a Working Hypothesis

The proposed transverse mechanism can now be summarized.

A weak electromagnetic wave is assumed to possess a small inward component of energy transport arising from differences between the spatial distributions of its electric and magnetic fields.

Contraction increases the electromagnetic energy density and the characteristic field amplitudes.

As the fields approach their proposed saturated state, their spatial organization changes. At saturation, the radial tendency is hypothesized to vanish, allowing the transverse dimensions to remain approximately constant.

If additional energy produces temporary oversaturation, a reversal of the radial response may enlarge the wave's transverse structure until the characteristic amplitudes are restored.

The resulting equilibrium radius may therefore depend on the energy contained in the wave.

The mechanism offers a possible explanation for how electromagnetic waves of different energies could maintain similar saturated field amplitudes while possessing different transverse dimensions.

The following chapters examine a complementary aspect of the proposed structure: the periodic transformation of the electromagnetic field through an intermediate configuration associated with Maxwell's displacement current, and the continuity of energy during this process.

4. Displacement Current and the Intermediate Field Configuration

The preceding chapters introduced a continuous electromagnetic wave with an approximately annular transverse field structure. The proposed wave undergoes periodic changes in its electric and magnetic field distributions while maintaining longitudinal propagation.

A central question is how the electromagnetic structure evolves between successive phases of the oscillation, particularly when the electric and magnetic contributions associated with the annular configuration become weak.

The present model assigns an important role to Maxwell's displacement current. It investigates whether the field configuration associated with displacement current can represent an intermediate phase of the same continuous electromagnetic process.

This interpretation does not introduce a new fundamental current or modify Maxwell's equations. It proposes a specific geometrical organization of the electromagnetic fields associated with their temporal variation.

4.1. Displacement Current in Maxwell's Equations

In vacuum, the displacement-current density is defined by

$$J_D = \epsilon_0 \frac{\partial E}{\partial t}$$

It describes the temporal variation of the electric field and enters the Ampère–Maxwell equation:

$$\nabla \times B = \mu_0 J_D$$

The displacement current is therefore directly connected to magnetic circulation.

A time-varying electric field and its associated magnetic field cannot be treated as independent structures. Their evolution is

constrained by the complete Maxwell equations.

The model considers the possibility that displacement current becomes especially important in describing the electromagnetic geometry during phases in which the annular electric-field contribution approaches its minimum.

In this interpretation, the displacement current is not an additional material flow. It is part of the electromagnetic field dynamics.

4.2. Quarter-Period Phase Relationship

Consider a sinusoidally varying electric-field component at a fixed position:

$$E(t) = E_0 \cos(\omega t)$$

Its displacement-current density is

$$J_D(t) = -\epsilon_0 \omega E_0 \sin(\omega t)$$

The displacement current is therefore shifted by one quarter of a period relative to the electric field.

When the electric-field component reaches its maximum, its instantaneous rate of change vanishes, and the corresponding displacement current is zero.

One quarter of a period later, the electric-field component passes through zero while the magnitude of its displacement current reaches a maximum:

$$J_{D,0} = \epsilon_0 \omega E_0$$

The same relationship applies at successive phases, with the signs changing according to the direction of field variation.

This phase relationship is a direct consequence of the definition of displacement current.

The proposed model interprets it as a possible temporal basis for periodic changes in the internal geometry of the electromagnetic wave.

A maximum in displacement current does not, by itself, demonstrate that the electromagnetic

energy has been transferred into a distinct spatial configuration. That interpretation requires an additional geometrical hypothesis, developed below.

4.3. The Intermediate Electromagnetic Configuration

The model proposes that the electromagnetic wave alternates between an approximately annular field configuration and an intermediate configuration associated with displacement current.

In the annular phase, the electric and magnetic fields are assumed to possess the transverse organization described in Section 2.

As this configuration evolves, the displacement-current distribution becomes increasingly important. The model considers the possibility that it forms an approximately axial distribution over a finite transverse region.

Through the Ampère–Maxwell relation, such a distribution is associated with a circulating magnetic field.

The intermediate configuration is therefore not represented by displacement current alone. It includes the complete electric and magnetic fields associated with this phase of the electromagnetic process.

Its spatial organization may differ from that of the annular configuration.

The proposed transformation may be represented schematically as

$$\text{Annular} \rightarrow \text{Intermediate} \rightarrow \text{Annular}$$

The sequence describes a periodic transformation of one continuous electromagnetic wave rather than the creation and destruction of separate electromagnetic objects.

The precise three-dimensional field profiles required for this transformation remain to be determined.

4.4. Magnetic Field Associated with the Intermediate Configuration

To illustrate the magnetic response associated with displacement current, consider an idealized approximately axial displacement-current distribution.

For a circular contour surrounding the propagation axis, the integral form of the Ampère–Maxwell equation gives

$$\oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 I_D$$

where the enclosed displacement current is obtained from the corresponding electric-field variation.

If the distribution is approximately axisymmetric, a circulating magnetic-field component may develop around the axis.

Its magnitude and radial profile depend on the actual spatial distribution of displacement current.

This is important for the proposed model because the intermediate configuration may possess a different magnetic-field geometry from the annular phase.

Such a difference could influence the transverse electromagnetic stress and the redistribution of energy during propagation.

However, the simplified axial-current picture should not be interpreted as a complete solution for a freely propagating electromagnetic wave.

The actual electric and magnetic field components must also satisfy Faraday's law, the divergence conditions, and local energy and momentum conservation.

4.5. Continuity Between Successive Half-Wavelength Regions

The electromagnetic wave is treated as a continuous structure with longitudinal periodicity determined by its wavelength.

Successive half-wavelength regions correspond to successive phases of the electromagnetic oscillation.

At the transition between neighboring regions, the annular field contribution may become weak while the intermediate configuration associated with displacement current becomes prominent.

The model proposes that this intermediate configuration provides electromagnetic continuity across the transition.

Consequently, the characteristic transverse organization of the wave need not disappear and be reconstructed independently at every half-wavelength boundary.

Instead, its internal field configuration evolves continuously from one phase into the next.

This provides a possible physical interpretation of how a structured electromagnetic wave maintains its longitudinal continuity while undergoing periodic changes in its transverse electromagnetic geometry.

The intermediate configuration may also connect neighboring regions that initially contain different amounts of electromagnetic energy.

The role of this connection in longitudinal energy redistribution is examined in Section 8.

4.6. Displacement Current and Energy Transport

Displacement current is central to the proposed intermediate configuration, but it must be distinguished from the electromagnetic energy flux.

The energy flux is determined by the Poynting vector:

$$\mathbf{S} = \frac{\mathbf{E} \times \mathbf{B}}{\mu_0}$$

Thus, the displacement-current density is not itself an energy flux. Its units and physical

definition differ from those of the Poynting vector.

Nevertheless, the field configuration associated with displacement current may participate in electromagnetic energy transport.

The proposed intermediate configuration contains electric and magnetic fields whose combined energy and momentum distributions must remain consistent with the propagation of the complete wave.

The model therefore assigns displacement current a structural and dynamical role in the transfer process without introducing an additional fundamental form of energy.

Its complementary energy contribution will be denoted by u_j and defined through the energy balance in the following chapter.

This quantity represents energy assigned to the intermediate electromagnetic configuration, not an independent energy density proportional simply to the square of displacement current.

4.7. The Intermediate Configuration as a Working Hypothesis

The quarter-period relationship between the electric field and displacement current follows directly from Maxwell's equations.

The proposed transformation between an annular field configuration and an approximately axial intermediate configuration is an additional hypothesis concerning the three-dimensional organization of the electromagnetic wave.

Its purpose is to provide a possible geometrical interpretation of the continuity of the wave during successive electromagnetic phases.

If the hypothesis is valid, the intermediate configuration may serve two related functions.

First, it may participate in maintaining the transverse electromagnetic structure as the annular configuration periodically changes.

Second, it may provide a continuous electromagnetic connection through which neighboring half-wavelength regions exchange energy and adjust their transverse dimensions.

The following chapter examines the corresponding energy balance and defines the complementary energy associated with the proposed intermediate configuration

5. Periodic Energy Exchange

The preceding chapter introduced the hypothesis that electromagnetic-wave propagation involves a periodic transformation between an approximately annular field configuration and an intermediate configuration associated with Maxwell's displacement current.

If these configurations represent successive phases of one continuous electromagnetic process, their transformation must preserve electromagnetic energy.

The present chapter develops an idealized energy description of this process. It introduces a complementary energy contribution associated with the intermediate configuration and examines how energy may be redistributed during successive phases of the electromagnetic oscillation.

The proposed description does not introduce a new fundamental form of energy. Rather, it separates the total electromagnetic energy into contributions assigned to different phases and geometrical configurations of the same continuous field.

5.1. Electromagnetic Energy Density

In vacuum, electromagnetic energy is stored in the electric and magnetic fields.

The total electromagnetic energy density is

$$u_{\text{tot}} = \frac{\epsilon_0 E_{\text{tot}}^2}{2} + \frac{B_{\text{tot}}^2}{2\mu_0}$$

Here, the total fields include all electric and magnetic contributions present at the considered position and time.

The total electromagnetic energy contained in a selected volume is obtained by integrating this density:

$$W_{\text{tot}} = \int_V u_{\text{tot}} dV$$

In the proposed wave model, the spatial organization of the fields changes periodically. Consequently, the distribution of energy between the annular and intermediate configurations may change even when the total energy remains constant.

To describe this transformation, the model introduces separate energy contributions associated with the two configurations.

These contributions represent a decomposition of the complete electromagnetic energy and must not be interpreted as independent additions to it.

5.2. Energy of the Annular Configuration

The approximately annular configuration is characterized by the electric and magnetic field distributions introduced in Section 2.

Their assigned energy densities are denoted by u_E and u_B .

For the purpose of the model, these quantities describe the energy attributed to the annular configuration, rather than necessarily representing the entire electric and magnetic energy of the complete wave.

The corresponding energy contained in a selected volume is

$$W_{EB} = W_E + W_B$$

During the electromagnetic oscillation, the annular configuration is assumed to evolve periodically.

Its energy contribution may consequently increase and decrease as the field structure transforms.

The reduction of this contribution does not imply that the corresponding energy disappears. Instead, the model proposes that it becomes associated with the intermediate electromagnetic configuration.

5.3. Complementary Energy Associated with Displacement Current

The intermediate configuration is linked to Maxwell's displacement current and the electric and magnetic fields associated with its spatial organization.

Its complementary energy density is denoted by u_J .

The model defines this quantity as the difference between the total electromagnetic energy density and the contributions assigned to the annular configuration:

$$u_J = u_{\text{tot}} - u_E - u_B$$

Accordingly, the local energy balance is

$$u_{\text{tot}} = u_E + u_B + u_J$$

The corresponding integrated energy balance is

$$W_{\text{tot}} = W_E + W_B + W_J$$

This definition provides a simple description of the proposed energy redistribution.

The subscript J identifies the connection with the displacement-current configuration. It does not imply that displacement current itself possesses an additional fundamental energy density independent of the electromagnetic field.

The energy assigned to the intermediate configuration must ultimately be accounted for by the complete electric and magnetic fields.

In particular, u_J must not be added to an expression that already includes the complete Maxwell energy density of all fields. Such a procedure would count the same electromagnetic energy twice.

The decomposition is therefore meaningful only when the annular and complementary contributions are consistently defined.

5.4. Complementary Temporal Dependence

Consider an idealized periodic transformation in which the energy assigned to the annular configuration varies according to

$$W_{EB}(t) = W_0 \cos^2(\omega t)$$

Here, W_0 denotes the total energy of the selected wave region in the absence of net energy exchange with neighboring regions.

The complementary energy assigned to the intermediate configuration is then

$$W_J(t) = W_0 \sin^2(\omega t)$$

Their sum remains constant:

$$W_{EB}(t) + W_J(t) = W_0$$

This representation expresses the central energetic hypothesis of the model.

When the annular contribution decreases, the intermediate contribution increases by the same amount. When the intermediate contribution decreases, the annular contribution increases correspondingly.

The two contributions are complementary phases of one electromagnetic process.

The sinusoidal-squared dependence is an idealized representation motivated by the quarter-period relationship between the electric field and displacement current. It does not constitute an independent derivation of the energy contained in the intermediate configuration.

5.5. Energy Exchange During One Half-Period

The proposed transformation can be followed through successive phases of the oscillation.

At the beginning of the idealized cycle, the annular contribution is maximal and the complementary contribution vanishes.

As the phase advances, energy is progressively reassigned from the annular configuration to the intermediate configuration.

After one eighth of a period, the two energy contributions are equal.

One quarter of a period after the initial maximum, the complementary contribution reaches its maximum while the annular contribution reaches its minimum.

The transformation then reverses.

Phase	Annular energy	Intermediate energy
Initial maximum	W_0	0
One eighth of a period	$W_0/2$	$W_0/2$
One quarter of a period	0	W_0
One half of a period	W_0	0

The quantities in this table represent the proposed integrated energy contributions, not necessarily the local energy densities at every position within the wave.

The model therefore describes an oscillation in the relative contributions of two electromagnetic configurations while preserving their total energy.

5.6. Displacement Current and the Rate of Energy Exchange

For a sinusoidally varying electric-field component, displacement current is shifted by one quarter of a period relative to the field itself.

This temporal relationship provides a possible basis for the complementary transformation proposed above.

In the idealized energy representation, the rate of change of the annular contribution is

$$\frac{dW_{EB}}{dt} = -\omega W_0 \sin(2\omega t)$$

The intermediate contribution changes at the opposite rate:

$$\frac{dW_J}{dt} = \omega W_0 \sin(2\omega t)$$

Consequently, their combined rate of change vanishes:

$$\frac{dW_{EB}}{dt} + \frac{dW_J}{dt} = 0$$

The energy-exchange rate is zero when either contribution reaches its maximum. Its magnitude is greatest when the two contributions are equal.

The model interprets this behavior as a continuous transformation between the annular and intermediate electromagnetic configurations.

However, the relationship between displacement-current amplitude and the actual transferred electromagnetic power remains to be derived from the complete field dynamics.

In particular, the magnitude of J_D alone does not determine the energy-transfer rate.

5.7. Conservation of Energy and Longitudinal Transport

The preceding expressions describe an idealized selected wave region whose total energy is constant.

A propagating electromagnetic wave, however, continuously transports energy through space. Energy may enter or leave a particular region, including through its longitudinal boundaries.

The local conservation law is expressed by Poynting's theorem:

$$\frac{\partial u_{\text{tot}}}{\partial t} + \nabla \cdot \mathbf{S} = 0$$

This form applies in vacuum in the absence of work done on material charges.

It shows that a local change in electromagnetic energy density must be accompanied by an appropriate divergence of the energy flux.

The total energy of a selected region therefore remains constant only when its net electromagnetic energy flux vanishes.

For a region containing one half-wavelength of the proposed wave, energy exchange with neighboring regions may modify its instantaneous total energy.

The model consequently distinguishes between two processes: periodic redistribution between the annular and intermediate configurations, and longitudinal redistribution between adjacent half-wavelength regions.

Both processes must satisfy electromagnetic energy conservation.

5.8. Energy Continuity in the Proposed Wave Structure

The complementary energy description provides a possible interpretation of how the electromagnetic wave maintains continuity during periodic changes in its internal configuration.

As the annular energy contribution decreases, the proposed intermediate configuration becomes more prominent.

The total electromagnetic energy need not disappear when the annular contribution reaches its minimum.

Likewise, the characteristic transverse organization of the wave need not be reconstructed independently at the beginning of every half-wavelength region.

The model proposes that the intermediate configuration provides a continuous electromagnetic connection between successive phases.

This connection may also allow neighboring regions with different energies to influence one another.

Nevertheless, conservation of the integrated energy alone does not establish the detailed spatial distribution of the intermediate configuration or its ability to preserve a particular transverse radius.

A complete demonstration requires electromagnetic fields satisfying Maxwell's equations and the corresponding energy and momentum balances.

The following chapter examines energy continuity during propagation, with particular attention to the relationship between the longitudinal and transverse dimensions of the proposed electromagnetic wave.

6. Energy Continuity During Propagation

The preceding chapter introduced a complementary energy description of the proposed electromagnetic wave. During its periodic evolution, the energy assigned to the annular configuration decreases as the contribution assigned to the intermediate configuration increases, and vice versa.

This representation provides an idealized description of energy exchange within the evolving field structure.

Electromagnetic propagation, however, requires more than conservation of energy within an isolated region. Energy must also be transported continuously along the propagation axis.

The present chapter examines how the proposed annular and intermediate configurations may participate in this process and how the electromagnetic structure can remain continuous across successive half-wavelength regions.

6.1. Energy Conservation in a Propagating Wave

The electromagnetic energy density in vacuum is determined by the complete electric and magnetic fields.

Its local conservation is described by Poynting's theorem:

$$\frac{\partial u_{\text{tot}}}{\partial t} + \nabla \cdot \mathbf{S} = 0$$

The Poynting vector describes the direction and magnitude of electromagnetic energy transport.

For the proposed approximately axisymmetric wave structure, the energy flux may possess longitudinal and radial components.

In cylindrical coordinates, the conservation equation can therefore be written as

$$\frac{\partial u_{\text{tot}}}{\partial t} + \frac{1}{r} \frac{\partial(rS_R)}{\partial r} + \frac{\partial S_z}{\partial z} = 0$$

Here, S_z describes longitudinal energy transport, while S_R describes radial energy redistribution.

This equation shows that longitudinal and transverse changes in the electromagnetic energy distribution are connected.

A local increase in energy density may result from longitudinal inflow, radial inflow, or both. Conversely, a local decrease must be accompanied by an appropriate energy outflow.

The proposed geometry of the electromagnetic wave must satisfy this conservation law throughout its periodic evolution.

6.2. Periodic Transformation During Propagation

The electromagnetic wave is assumed to propagate along the z-axis while its internal field configuration changes periodically.

Its longitudinal periodicity is characterized by the wavelength λ , while the corresponding temporal period is determined by its frequency.

In vacuum, the conventional propagation relation is

$$c = \lambda f$$

The model distinguishes this longitudinal periodicity from the transverse dimensions of the electromagnetic structure.

Successive regions of length $\lambda/2$ represent successive half-periods of the oscillation.

Within the proposed interpretation, each such region undergoes a transformation between an approximately annular configuration and an intermediate configuration associated with displacement current.

The transformation does not require the electromagnetic energy to disappear at the transition between successive regions.

Instead, energy may be redistributed between the two configurations while continuing to propagate along the wave.

The model therefore treats the electromagnetic wave as one continuous field structure rather than as a sequence of independently reconstructed objects.

6.3. The Intermediate Configuration at Half-Wavelength Transitions

Consider the transition between two successive half-wavelength regions.

In the idealized periodic description, the energy assigned to the annular configuration may approach its minimum at this transition.

The complementary contribution associated with the intermediate configuration then approaches its maximum.

The corresponding energy balance is

$$W_{\text{tot}} = W_E + W_B + W_J$$

When the annular contribution is minimal, the proposed model assigns the remaining electromagnetic energy to the intermediate configuration.

This provides a possible explanation for how the internal electromagnetic structure remains continuous during the transition.

The intermediate configuration is linked to the displacement-current distribution and its associated electric and magnetic fields.

Its role is not to introduce a separate carrier of energy independent of electromagnetism. Rather, it represents a complementary organization of the same electromagnetic field.

In this interpretation, successive half-wavelength regions may contribute to a common intermediate configuration.

The transition is therefore not regarded as a boundary between two physically disconnected structures.

The energy and geometry of the wave evolve continuously across it.

6.4. Longitudinal Energy Transport Through the Intermediate Configuration

The proposed intermediate configuration is associated with a time-varying electric field and the corresponding magnetic circulation.

These fields can participate in electromagnetic energy transport.

The actual energy flux remains determined by the Poynting vector:

$$S = \frac{E \times B}{\mu_0}$$

For the proposed wave structure, the dominant energy transport is longitudinal.

The model hypothesizes that the intermediate configuration provides a continuous electromagnetic connection through which energy can pass from one half-wavelength region to the next.

This interpretation assigns displacement current an important role in the dynamics of the transfer without identifying the current density itself with an energy flux.

A complete calculation would require the electric and magnetic field components of the intermediate configuration.

In particular, the longitudinal component of the Poynting vector must be obtained from the complete fields present at the transition.

6.5. Energy of a Selected Half-Wavelength Region

Let W_n denote the electromagnetic energy associated with the $n - th$ half-wavelength region.

The energy of this region may change if the longitudinal power entering it differs from the power leaving it.

Its energy balance can be written as

$$\frac{dW_n}{dt} = P_{n-1} - P_n$$

Here, P_{n-1} denotes the power entering the region from the preceding half-wavelength region, while P_n denotes the power transferred toward the following region.

This simplified expression assumes that net radial energy exchange with the exterior of the selected region is negligible.

If radial exchange is significant, its contribution must also be included in the balance.

In a steady periodic state, the incoming and outgoing powers are equal.

Consequently, the energy of the selected region remains constant even though electromagnetic energy continuously passes through it.

If the two powers differ, the region temporarily gains or loses energy.

This distinction is important for the proposed model because successive half-wavelength

regions need not initially contain equal amounts of electromagnetic energy.

The possibility that their common intermediate configuration promotes energy redistribution is examined in Section 8.

6.6. Continuity of the Transverse Structure

Energy continuity is accompanied by a separate question concerning the transverse organization of the electromagnetic wave.

The model assumes that the annular and intermediate configurations are successive phases of a connected field structure.

As the annular contribution decreases, the intermediate configuration may retain information about the transverse distribution of the electromagnetic field through its own spatial organization.

Consequently, the characteristic transverse radius need not be selected independently at the beginning of every half-wavelength region.

However, conservation of energy alone does not establish the constancy of that radius.

The electromagnetic momentum distribution must also evolve consistently across the transition.

The proposed model therefore requires the intermediate configuration to participate in both energy continuity and the preservation or adjustment of transverse geometry.

If neighboring regions possess different transverse dimensions, their shared intermediate configuration may contribute to the redistribution of energy and the gradual adjustment of their field profiles.

6.7. Independence of Longitudinal and Transverse Scales

The longitudinal and transverse dimensions of the proposed electromagnetic wave describe different aspects of its organization.

The wavelength determines the spatial periodicity of the electromagnetic oscillation.

The transverse radius and effective radial thickness describe the spatial concentration of electromagnetic energy around the propagation axis.

The model does not assume a universal proportionality between these quantities.

In particular, the proposed saturated amplitudes and transverse dimensions are not determined by the propagation relation alone.

A wave may possess a different transverse geometry or field amplitude while retaining the same longitudinal wavelength and frequency.

This distinction follows the separation introduced in the earlier chapters between electromagnetic propagation and the possible existence of a preferred transverse configuration.

The conditions governing transverse saturation and stability are examined in Section 7.

6.8. Energy Continuity as a Structural Principle

The proposed model combines two forms of electromagnetic continuity.

The first is the periodic redistribution of energy between the annular and intermediate configurations.

The second is the longitudinal transport of energy between successive half-wavelength regions.

These processes are related but should not be confused.

The complementary energy description accounts for the proposed internal transformation of the field structure, while the Poynting vector describes its actual electromagnetic energy transport.

The intermediate configuration associated with displacement current is hypothesized to connect the successive phases of this process and to contribute to the continuity of the wave's transverse organization.

The model therefore offers a possible physical interpretation of a continuously propagating electromagnetic wave whose internal geometry changes periodically without requiring the destruction and reconstruction of independent electromagnetic objects.

The proposed interpretation remains subject to the complete Maxwell equations and the conservation of electromagnetic energy and momentum.

The following chapter examines how such a continuous structure might respond to changes in its energy content and whether a dynamically regulated transverse geometry can emerge through the proposed saturation mechanism.

7. Saturation and Energy-Dependent Transverse Geometry

The preceding chapters introduced a continuous electromagnetic wave whose internal field configuration undergoes periodic transformations while preserving electromagnetic energy. The proposed intermediate configuration associated with displacement current provides a possible connection between successive phases of this process.

A separate question concerns the transverse dimensions of the wave.

Maxwell's equations permit electromagnetic fields of different amplitudes to propagate in vacuum, but they do not independently select a unique transverse radius or a universal field amplitude. The present model therefore introduces a hypothetical saturation mechanism through which the internal electromagnetic structure may regulate its characteristic field amplitudes and transverse dimensions.

The central proposal is that saturation is primarily associated with characteristic electric and magnetic field amplitudes rather than a single universal transverse radius.

Consequently, electromagnetic waves containing different amounts of energy may possess different transverse dimensions while maintaining approximately the same saturated field amplitudes.

7.1. Transverse Geometry and Electromagnetic Energy

The proposed electromagnetic wave possesses an approximately annular region of concentrated electromagnetic energy.

Its characteristic transverse geometry is described by the radius R and the effective radial thickness a .

For an individual half-wavelength region, the total electromagnetic energy depends on the field amplitudes and their spatial distributions.

In the full electromagnetic description, this energy must include the complete electric and magnetic fields, including the contribution assigned in the proposed model to the intermediate configuration associated with displacement current.

For a family of geometrically similar field profiles, the energy may be approximated by

$$W = C\lambda\epsilon_0 E^2 R^2$$

Here, C is a dimensionless geometrical coefficient that incorporates the effective transverse width, longitudinal field distribution, and complete electromagnetic energy represented by the chosen approximation.

The relation assumes a nearly constant relative thickness a/R and a comparable relationship between the characteristic electric and magnetic amplitudes.

It is not a universal expression for an arbitrary field configuration.

The approximation nevertheless provides a useful starting point for investigating how energy, amplitude, and transverse radius may be related.

7.2. Geometrical Asymmetry in an Undersaturated Wave

The proposed mechanism begins with a small difference between the spatial distributions of the electric and magnetic fields.

Their characteristic radial positions, widths, and gradients need not be identical.

The model assumes that this asymmetry may exist even when the electromagnetic wave is relatively weak.

Because the Poynting vector depends on the vector product of the electric and magnetic fields, changes in their spatial organization may influence the direction of electromagnetic energy transport.

In an undersaturated wave, the model hypothesizes a small inward radial component:

$$S_R < 0$$

The dominant energy transport remains longitudinal, while the radial component is assumed to contribute to the contraction of the transverse structure.

The proposed contraction mechanism does not require the field amplitudes to have already reached their saturated values.

Instead, it provides a possible process through which an initially broad and weak electromagnetic wave may progressively concentrate its energy.

The actual direction of the radial energy flux cannot yet be calculated because the complete three-dimensional electric and magnetic field profiles remain unknown.

The proposed connection between field asymmetry and contraction therefore remains a geometrical and dynamical hypothesis.

7.3. Increase of Field Amplitude During Contraction

Consider an undersaturated electromagnetic wave whose transverse radius decreases while the energy contained in a selected region remains approximately constant.

Under the geometrical approximation introduced in Section 7.1, the characteristic electric-field amplitude increases as the radius decreases.

At fixed energy and wavelength, the relation becomes

$$E \propto \frac{1}{R}$$

If the characteristic electric and magnetic amplitudes maintain the approximate relationship

$$E = cB$$

the magnetic amplitude increases together with the electric amplitude.

Thus, the proposed inward radial response can increase the local energy density without requiring additional energy to enter the selected region.

The contraction may continue until the field configuration approaches a state in which its spatial organization changes sufficiently to reduce the inward radial tendency.

The model identifies this possible state with electromagnetic saturation.

This process should be distinguished from the transfer of energy between neighboring half-wavelength regions, which may occur simultaneously during propagation.

7.4. The Saturated Field State

The model introduces a hypothetical saturated state characterized by the amplitudes E_0 and B_0 .

For the corresponding propagating field components, their approximate relationship is

$$E_0 = cB_0$$

The proposed saturated state is defined by the condition that the characteristic field amplitudes remain approximately constant during steady propagation.

At saturation, the model hypothesizes that the relative spatial distributions of the electric and magnetic fields produce no net radial tendency toward contraction or expansion.

The corresponding radial component of the Poynting vector is assumed to approach zero:

$$S_R \approx 0$$

The electromagnetic energy flux is then predominantly longitudinal.

This condition represents the proposed geometrical equilibrium of the wave. It does not, by itself, constitute a complete electromagnetic momentum-balance calculation.

The characteristic saturated amplitudes have not been derived from Maxwell's equations.

Their existence, magnitude, and possible universality remain hypotheses of the model.

In particular, saturation should not be interpreted as a fundamental upper limit imposed on the electric or magnetic field by classical electrodynamics.

7.5. Oversaturation and Transverse Expansion

Consider a saturated electromagnetic wave that receives additional energy while its transverse dimensions initially remain approximately unchanged.

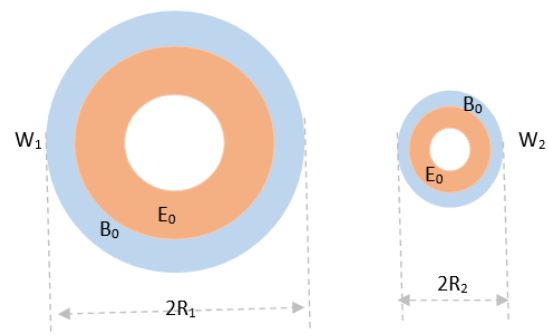


Figure 3. Schematic comparison of two saturated electromagnetic-wave regions with different energies and transverse radii. Both regions are assumed to possess the same characteristic saturated electric and magnetic field amplitudes E_0 and B_0 . The region containing more energy has a larger transverse radius. For geometrically similar field profiles at a fixed wavelength, the model predicts that the energy scales approximately with the square of the radius. The illustration represents a proposed family of saturated configurations rather than independently established electromagnetic structures.

Its energy density increases, causing the characteristic field amplitudes to rise above their proposed saturated values.

The model describes this temporary condition as oversaturation.

Oversaturation is hypothesized to change the relative spatial organization of the electric and magnetic fields.

The resulting field asymmetry may reverse the radial component of the Poynting vector:

$$S_R > 0$$

The energy flux is then directed slightly outward.

If the corresponding electromagnetic momentum balance produces an expansive response, the transverse radius increases.

The additional energy is consequently distributed over a larger effective volume.

As the transverse dimensions increase, the characteristic field amplitudes may decrease toward their saturated values.

The proposed mechanism therefore allows an electromagnetic wave to accommodate additional energy without requiring a permanent increase in its characteristic field amplitudes.

In this interpretation, oversaturation is a temporary departure from the saturated state, while the saturated state represents the proposed dynamically regulated configuration.

7.6. Energy-Dependent Saturated Radius

An important consequence of the proposed saturation mechanism is that a common characteristic amplitude does not require a common transverse radius.

For a saturated wave, the approximate energy relation becomes

$$W = C\lambda\epsilon_0 E_0^2 R_{eq}^2$$

At a fixed wavelength, for comparable field profiles and a common saturated amplitude, the equilibrium radius is

$$R_{eq} = \sqrt{\frac{W}{C\lambda\epsilon_0 E_0^2}}$$

Consequently, the equilibrium radius scales with the square root of the energy:

$$R_{eq} \propto \sqrt{W}$$

A wave containing more energy may therefore possess a larger transverse radius while maintaining approximately the same characteristic electric and magnetic amplitudes.

For two saturated wave regions at the same wavelength, the corresponding radii satisfy

$$\frac{R_2}{R_1} = \sqrt{\frac{W_2}{W_1}}$$

If the second region contains four times the energy of the first, its equilibrium radius is twice as large under the stated geometrical assumptions.

The model thus permits a family of energy-dependent transverse geometries.

It does not require every electromagnetic wave to converge toward one universal radius R_0 .

The proportionality also depends on the effective geometrical coefficient C . If the radial thickness or field profiles change significantly with energy, the simple square-root relationship must be modified.

7.7. Saturation as Regulation of Field Amplitude

The distinction between energy and field amplitude can be expressed through small changes in the approximate energy relation.

For fixed wavelength and geometrical coefficient, its differential form is

$$\frac{dW}{W} = 2 \frac{dE}{E} + 2 \frac{dR}{R}$$

If additional energy is accommodated through transverse expansion while the electric amplitude remains at its saturated value, then

$$\frac{dE}{E} = 0$$

The energy change is consequently related to the radius change by

$$\frac{dR}{R} = \frac{1}{2} \frac{dW}{W}$$

This result shows how the proposed saturated state can accommodate different energies while maintaining a constant characteristic field amplitude.

Saturation therefore concerns the amplitude of the electromagnetic fields, not the maximum total energy that an electromagnetic wave may contain.

The mathematical relation is consistent with the proposed geometrical adjustment, although the physical mechanism selecting and maintaining the saturated amplitude remains to be established.

7.8. Stability of the Saturated Configuration

A saturated electromagnetic wave must respond consistently to small deviations from its equilibrium geometry.

Consider a wave with fixed energy W and equilibrium radius $R_e q$.

If its radius increases slightly, the characteristic field amplitudes decrease below their saturated values.

The model then predicts an inward radial response that tends to restore the equilibrium radius.

Conversely, if the radius decreases, the field amplitudes increase above their saturated values.

The resulting oversaturated configuration is hypothesized to produce an outward radial response.

This provides a possible restoring mechanism around the saturated state.

However, a complete demonstration requires more than the assumed change in the direction of energy transport.

The electromagnetic momentum balance must show that the corresponding stresses generate a restoring radial response.

The model therefore treats saturation as a candidate mechanism of transverse stability rather than an established consequence of the Maxwell equations.

7.9. Longitudinal Energy Redistribution and Transverse Adjustment

The proposed wave contains successive half-wavelength regions that may temporarily possess different energies and transverse dimensions.

If two neighboring regions are initially saturated but contain different energies, they may have different equilibrium radii.

An exchange of energy between them can temporarily change their field amplitudes.

The region that loses energy becomes undersaturated and may contract.

The region that gains energy becomes oversaturated and may expand.

Through these responses, both regions may approach new saturated configurations corresponding to their redistributed energies.

The model proposes that the intermediate electromagnetic configuration associated with displacement current participates in this longitudinal energy exchange.

Consequently, energy redistribution and transverse adjustment may operate together to reduce differences between neighboring regions.

The detailed mechanism of their coupling, including the formation of a shared intermediate configuration, is developed in the following chapter.

7.10. Scope of the Saturation Hypothesis

The proposed saturation mechanism offers a possible interpretation of how an electromagnetic wave may regulate its transverse structure while accommodating different amounts of energy.

It distinguishes three states: undersaturation, saturation, and oversaturation.

An undersaturated wave is hypothesized to possess a small inward radial energy flux and a tendency toward contraction.

A saturated wave is characterized by approximately constant field amplitudes and a predominantly longitudinal energy flux.

An oversaturated wave is hypothesized to possess a small outward radial energy flux and a tendency toward expansion.

The model thereby allows different wave energies to correspond to different transverse radii without requiring different saturated field amplitudes.

Nevertheless, the existence of common characteristic amplitudes E_0 and B_0 , the proposed change in the radial direction of the

Poynting vector, and the stability of the resulting geometries remain to be established quantitatively.

The following chapter examines how longitudinal energy redistribution between neighboring half-wavelength regions may contribute to maintaining a coherent transverse structure during propagation.

8. Longitudinal Energy Redistribution and Structural Coherence

The preceding chapters introduced a continuous electromagnetic wave whose transverse structure may be regulated by a hypothetical saturation mechanism. Different amounts of energy can correspond to different equilibrium radii while the characteristic saturated field amplitudes remain approximately constant.

A further question arises when successive half-wavelength regions contain different amounts of energy.

If these regions formed completely independent electromagnetic objects, there would be no inherent mechanism ensuring continuity of their transverse dimensions. The proposed model instead treats them as successive phases of one continuous electromagnetic field.

Their common intermediate configuration, associated with displacement current, is hypothesized to provide a connection through which energy can be redistributed.

This chapter examines how such redistribution may influence the transverse geometry and contribute to the structural coherence of the propagating wave.

8.1. Successive Half-Wavelength Regions

Consider two neighboring half-wavelength regions of the same electromagnetic wave.

Their longitudinal dimensions are determined by the common wavelength, while their transverse dimensions may differ if they contain different amounts of energy.

Let their energies be W_1 and W_2 , and their characteristic transverse radii be R_1 and R_2 .

If both regions are initially saturated and possess geometrically similar field profiles, the approximate energy relation introduced in Section 7 gives

$$W_1 = C\lambda\epsilon_0 E_0^2 R_1^2$$

$$W_2 = C\lambda\epsilon_0 E_0^2 R_2^2$$

Consequently, different energies may correspond to different transverse radii, even when the characteristic field amplitudes are equal.

Such a difference does not imply that the two regions are physically disconnected. They remain parts of the same continuous electromagnetic wave.

The model proposes that their electromagnetic coupling may reduce local differences in energy and transverse geometry.

8.2. Overlapping Fields and Electromagnetic Coupling

Electromagnetic fields do not terminate abruptly at the boundaries of a geometrically defined half-wavelength region.

The fields associated with neighboring regions may therefore overlap, particularly near their common transition.

In the overlap region, the complete electric and magnetic fields are obtained from their respective contributions:

$$E_{\text{tot}} = E_1 + E_2$$

$$B_{\text{tot}} = B_1 + B_2$$

The corresponding electromagnetic energy density contains contributions associated with both regions, together with terms arising from their superposition.

For the electric field, this can be expressed as

$$u_{E,\text{tot}} = \frac{\epsilon_0}{2} (E_1^2 + E_2^2 + 2E_1 \cdot E_2)$$

An analogous expression applies to the magnetic field.

The additional terms depend on the relative orientation and phase of the neighboring field contributions.

This shows that their combined electromagnetic energy need not be described by the simple sum of two independently assigned energies in the region where the fields overlap.

The proposed model interprets this coupling as a possible basis for energy redistribution between neighboring half-wavelength regions.

The decomposition into individual regions is a useful description of the wave's periodic structure. It must not be interpreted as an additional physical boundary within the continuous field.

8.3. Shared Intermediate Configuration

The proposed intermediate configuration becomes especially important near transitions between successive half-wavelength regions.

As described in Sections 4–6, the annular energy contribution may approach its minimum while the complementary contribution associated with displacement current becomes prominent.

The model proposes that the preceding and following half-wavelength regions participate in the formation of a shared intermediate electromagnetic configuration.

This configuration is associated with their combined displacement-current dynamics and the corresponding electric and magnetic fields.

If the neighboring regions have different transverse radii, their contributions to the shared configuration may also possess different radial distributions.

The resulting intermediate configuration may therefore develop a transverse energy profile that differs from either contribution considered separately.

Its characteristic radius is not assumed to be predetermined.

Instead, it must depend on the field profiles, relative phases, and energies of the participating regions.

The model proposes that this shared configuration provides a possible mechanism for transferring energy between neighboring regions while maintaining the continuity of the electromagnetic wave.

The detailed three-dimensional structure of the shared configuration remains to be determined.

8.4. Longitudinal Energy Redistribution

Let the first half-wavelength region initially contain more energy than the second:

$$W_1 > W_2$$

The proposed coupling allows part of the energy associated with the first region to be transferred to the second.

Denoting the transferred amount by ΔW , their energies after the exchange are

$$W'_1 = W_1 - \Delta W$$

$$W'_2 = W_2 + \Delta W$$

If there is no net exchange with other regions or the surroundings, their combined energy remains constant:

$$W'_1 + W'_2 = W_1 + W_2$$

This relation expresses energy conservation during the proposed redistribution.

The model hypothesizes that differences between neighboring intermediate configurations can contribute to such an exchange.

However, the direction and magnitude of the actual electromagnetic energy flux must ultimately be calculated from the complete electric and magnetic fields.

Energy conservation establishes the balance between the regions but does not independently determine the amount transferred during a particular oscillation.

For the purposes of the present model, it is sufficient to identify a possible continuous electromagnetic connection and the consequences of energy redistribution for the transverse structure.

8.5. Response of the Neighboring Regions

Suppose both regions are initially saturated.

The transfer of energy modifies their energy contents before their transverse dimensions have fully adjusted.

The region losing energy becomes temporarily undersaturated.

Its characteristic field amplitudes decrease below their proposed saturated values, and the model predicts a tendency toward transverse contraction.

Conversely, the region gaining energy becomes temporarily oversaturated.

Its field amplitudes increase above the saturated values, and the model predicts a tendency toward transverse expansion.

After their geometrical adjustment, both regions may return toward their saturated field amplitudes while possessing new equilibrium radii.

For geometrically similar saturated configurations, these radii satisfy

$$R'_1 = \sqrt{\frac{W'_1}{C\lambda\epsilon_0 E_0^2}}$$

$$R'_2 = \sqrt{\frac{W'_2}{C\lambda\epsilon_0 E_0^2}}$$

Thus, redistribution of energy may reduce the difference between the neighboring transverse dimensions.

In the proposed interpretation, energy exchange and geometrical adjustment are coupled processes. They need not occur as two completely separate stages.

8.6. Common Transverse Geometry

If the energies of two neighboring saturated regions become equal, their equilibrium radii also become equal under the same geometrical assumptions.

For an idealized isolated pair, complete energy equalization would give

$$W_{eq} = \frac{W_1 + W_2}{2}$$

The corresponding common radius is

$$R_{eq} = \sqrt{\frac{R_1^2 + R_2^2}{2}}$$

This result illustrates how the proposed combination of longitudinal energy redistribution and transverse saturation can lead to a common geometry.

It is not necessary to assume that the shared intermediate configuration initially possesses this exact radius.

Its actual shape may evolve during the exchange, and complete equalization may require more than one oscillation.

The rate of this process depends on the electromagnetic coupling and remains undetermined.

The same principle may extend to a sequence of many neighboring half-wavelength regions, allowing local differences in their transverse dimensions to be reduced during propagation.

8.7. Energy Transport and the Poynting Vector

The proposed shared intermediate configuration must also be consistent with electromagnetic energy transport.

The Poynting vector describes the energy flux associated with the complete fields:

$$\vec{S} = \frac{\vec{E}_{tot} \times \vec{B}_{tot}}{\mu_0}$$

When neighboring regions have different field profiles, their combined configuration may modify both the longitudinal and radial components of this flux.

The model therefore allows the possibility that energy redistribution between neighboring regions is accompanied by transverse adjustment of the electromagnetic field.

The direction of this additional flux cannot be determined from the difference in their scalar energy densities alone.

It depends on the complete vector fields, including their relative orientations and phases.

The proposed coupling through the intermediate configuration provides a possible mechanism for such redistribution, but a quantitative calculation requires explicit three-dimensional fields satisfying Maxwell's equations.

8.8. Coherence of the Continuous Electromagnetic Wave

The longitudinal coupling of neighboring regions is proposed to contribute to the coherence of the complete electromagnetic wave.

In this context, coherence refers to the preservation of a connected electromagnetic structure with consistent longitudinal periodicity and a potentially more uniform transverse organization.

The model does not require every region to contain exactly the same energy at every instant.

Temporary differences may arise through interactions or other disturbances.

If the proposed redistribution mechanism operates, such differences can influence neighboring regions and may diminish during subsequent evolution.

Their common intermediate configuration provides a possible physical connection between local changes in energy and adjustments of transverse geometry.

The resulting wave is therefore described as a continuous electromagnetic structure rather than a sequence of independent toroidal objects.

This interpretation is compatible with the model's distinction between longitudinal propagation and transverse structural regulation.

It does not, however, establish the existence of a self-confined electromagnetic wave in vacuum. That question requires a complete field and momentum-balance solution.

8.9. Energy Redistribution and Quantization

The proposed energy redistribution should not be confused with energy quantization.

The model allows electromagnetic energy to be transferred between neighboring regions while the total energy is conserved.

The amount transferred is not assumed to be a universal quantum.

Likewise, the proposed saturated field amplitudes do not by themselves establish a discrete set of allowed wave energies.

Different energies may correspond to different transverse dimensions within the approximate geometrical description.

Whether additional structural conditions can restrict these configurations to particular energies is a separate question.

The present chapter therefore concerns electromagnetic coupling and structural coherence, not a derivation of photon energy or the photoelectric relation.

The interaction between electromagnetic radiation and matter is considered separately.

8.10. Scope of the Proposed Coupling Mechanism

The model proposes that successive half-wavelength regions are connected through their common electromagnetic fields, particularly during the intermediate configuration associated with displacement current.

This connection may allow regions with different energies to exchange energy.

The corresponding departures from saturation can produce transverse responses that reduce differences in their characteristic radii.

The proposed mechanism therefore provides a possible connection between longitudinal energy redistribution and the maintenance of a coherent transverse wave structure.

Its detailed operation remains hypothetical. In particular, the spatial profiles of the shared intermediate configuration, the resulting Poynting vector, and the rate of energy equalization have not yet been derived.

The next chapter examines a related distinction: electromagnetic propagation itself does not require the wave to remain exactly in its proposed saturated transverse state.

9. Propagation Beyond the Saturated State

The preceding chapters introduced a hypothetical saturation mechanism through

which an electromagnetic wave may regulate its characteristic field amplitudes and transverse dimensions. Longitudinal energy redistribution between neighboring half-wavelength regions was proposed as an additional mechanism contributing to the continuity and coherence of its structure.

A separate question concerns whether electromagnetic propagation itself requires the wave to remain in the proposed saturated state.

Maxwell's equations do not impose such a requirement. Electromagnetic fields of different amplitudes can propagate in vacuum, and their propagation does not depend on the existence of a particular saturated field magnitude.

The present model therefore distinguishes between electromagnetic propagation and the possible dynamical regulation of the wave's transverse geometry.

9.1. Linearity of Maxwell's Equations

In vacuum, Maxwell's equations are linear in the electric and magnetic fields.

If a pair of fields represents a solution, multiplying both fields by the same constant produces another solution with the same spatial and temporal dependence.

Let the original fields be E and B . Their uniformly scaled counterparts are

$$E' = \alpha E$$

$$B' = \alpha B$$

where α is a constant scaling factor.

The scaled fields satisfy the same vacuum Maxwell equations as the original fields.

Consequently, the propagation relations do not select one particular electromagnetic amplitude.

The existence of a proposed saturated state must therefore be explained by additional

structural dynamics rather than by the linear propagation equations alone.

9.2. Scaling of Electromagnetic Energy

The energy density of an electromagnetic field depends quadratically on its electric and magnetic amplitudes.

When both fields are scaled by the same factor, their energy density becomes

$$u' = \alpha^2 u$$

If the spatial geometry is unchanged, the total energy contained in the corresponding region scales in the same way:

$$W' = \alpha^2 W$$

Thus, electromagnetic configurations with different amplitudes may possess different energies while satisfying the same fundamental propagation equations.

This result is independent of the proposed saturation mechanism.

It also shows that electromagnetic propagation cannot, by itself, establish the characteristic amplitudes E_0 and B_0 introduced in Section 7.

Their possible selection must arise from the additional geometrical and dynamical properties proposed by the model.

9.3. Propagation and Structural Saturation

The present model distinguishes two related but separate processes.

The first is longitudinal electromagnetic propagation, governed by the coupled evolution of the electric and magnetic fields.

The second is the proposed regulation of the wave's transverse structure through changes in its internal electromagnetic organization.

The longitudinal propagation relation remains

$$c = \lambda f$$

The proposed transverse mechanism concerns whether the field configuration can approach

and maintain characteristic saturated amplitudes while adjusting its transverse dimensions.

A wave may therefore continue to propagate even when its characteristic electric amplitude differs from E_0 .

Such a configuration is described within the model as undersaturated or oversaturated.

These terms refer to its proposed transverse structural state. They do not imply that the wave is unable to propagate.

9.4. Propagation of an Undersaturated Wave

Consider an electromagnetic wave whose characteristic field amplitudes are below their proposed saturated values.

The model assumes that small differences between the spatial distributions of its electric and magnetic fields may produce a weak inward radial component of energy transport.

This component is hypothesized to contribute to transverse contraction.

If the energy of a selected wave region remains approximately constant during the contraction, the characteristic field amplitudes increase as the effective transverse dimensions decrease.

The wave may consequently approach its proposed saturated state without interrupting longitudinal propagation.

However, the occurrence of this contraction is not a consequence of Maxwellian amplitude scaling.

It is an additional hypothesis concerning the transverse field geometry and electromagnetic momentum balance.

A complete description must establish whether the proposed field distributions generate the required restoring response.

9.5. Propagation of an Oversaturated Wave

An electromagnetic wave may also temporarily possess characteristic field amplitudes above the proposed saturated values.

Such a state may arise when a region receives additional energy before its transverse geometry has fully adjusted.

The model hypothesizes that oversaturation changes the spatial organization of the electric and magnetic fields, potentially reversing the radial component of energy transport.

The resulting outward response may increase the transverse dimensions and reduce the field amplitudes toward their saturated values.

Throughout this process, the electromagnetic wave may continue to propagate longitudinally.

The proposed transverse adjustment is therefore not a prerequisite for propagation, but a possible mechanism for maintaining a particular internal organization.

The detailed response remains to be established through the complete electromagnetic field and momentum equations.

9.6. The Saturated State and Different Wave Energies

In the proposed model, saturation concerns the characteristic field amplitudes rather than a universal total energy.

If different electromagnetic waves attain approximately the same saturated amplitudes, their total energies may still differ because their transverse dimensions differ.

For geometrically similar saturated configurations at a fixed wavelength, the approximate energy relation is

$$W = C\lambda\epsilon_0 E_0^2 R^2$$

Consequently, a larger saturated wave structure may contain more energy without

requiring a larger characteristic electric-field amplitude.

This distinction is important because it separates the proposed amplitude-regulation mechanism from the selection of a unique wave energy.

The model does not assume that saturation establishes a universal energy quantum.

Nor does it require all saturated electromagnetic waves to possess the same transverse radius.

The existence and possible universality of E_0 and B_0 remain hypotheses that require quantitative verification.

9.7. Relation Between Energy and Wavelength

The wavelength determines the longitudinal periodicity of the electromagnetic wave, while the proposed transverse geometry determines how its energy is distributed around the propagation axis.

These quantities are treated as distinct structural characteristics.

The approximate energy expression introduced above contains both the wavelength and the transverse radius.

9.8. Structural Stability as an Additional Hypothesis

The linearity of Maxwell's equations establishes that electromagnetic propagation is possible at different field amplitudes.

It does not establish that every geometrical field configuration is dynamically stable.

The proposed saturation mechanism addresses this additional question.

Within the model, the transverse organization of an electromagnetic wave may respond to deviations from its saturated state through changes in the radial distribution of electromagnetic energy and momentum.

Longitudinal coupling between neighboring half-wavelength regions may provide a further mechanism for redistributing energy and reducing local structural differences.

These mechanisms remain hypothetical until explicit field solutions demonstrate the required radial and longitudinal responses.

The central distinction is therefore preserved: electromagnetic propagation follows from Maxwell's equations, whereas the proposed maintenance of a saturated transverse structure requires additional dynamical justification.

The following chapter considers how the hypothesized internal organization of the electromagnetic wave may influence its interaction with matter, particularly through the relationship between field amplitude, frequency, and displacement-current dynamics.

10. Coherent Chain Termination and Growth by Reflection

A finite coherent electromagnetic structure cannot terminate through an abrupt discontinuity of the electromagnetic field. Near the end of the coherent chain, the last half-waves progressively lose the structural support provided by neighbouring half-waves. Their transverse radius therefore decreases smoothly toward zero.

In the interior of a stable coherent chain,

$$R_1 \approx R_2 \approx \dots \approx R_N \approx R_0$$

where R_0 represents the preferred transverse radius of the stable electromagnetic structure.

Near the end of the chain, however, the number of neighbouring half-waves decreases. The last half-waves therefore cannot maintain the same structural balance as those in the interior. Their transverse radii decrease progressively,

$$R_{N-2} < R_0$$

$$R_{N-1} < R_{N-2}$$

$$R_N \rightarrow 0$$

The end of the coherent electromagnetic wave is therefore not represented by an abrupt termination. It is a smooth spatial transition in which the transverse electromagnetic structure gradually contracts,

$$R(z) \rightarrow 0$$

This terminal region becomes particularly important during reflection.

When the leading part of a finite electromagnetic wave reaches a mirror, it is reflected while the following part of the same wave is still approaching the mirror. For a nearly normal reflection, the incident and reflected parts temporarily occupy the same spatial region and propagate in opposite directions.

Where the electric fields are locally in phase, the total electric-field amplitude can approach

$$E_{\text{tot}} = E_{\text{in}} + E_{\text{ref}} \approx 2E_0$$

The local electromagnetic energy distribution is therefore temporarily modified. Within the present model, an excess of energy in one half-wave disturbs the equilibrium with neighbouring half-waves.

For an undisturbed coherent chain,

$$W_1 \approx W_2 \approx \dots \approx W_N \approx W_0$$

where W_0 is the characteristic energy associated with an equilibrium half-wave.

During reflection, one local region may temporarily acquire

$$W_i = W_0 + \Delta W$$

while neighbouring regions remain closer to

$$W_{i-1} \approx W_{i+1} \approx W_0$$

This local imbalance creates a tendency for electromagnetic energy to redistribute toward neighbouring parts of the coherent chain. The

redistribution need not occur only toward the rear of the wave. It may propagate in both longitudinal directions,

$$W_i \rightarrow W_{i-1}, W_i, W_{i+1}$$

until a smoother local energy distribution is restored.

Within the present model, this redistribution is associated with a corresponding redistribution of the transverse radius. A half-wave carrying excess energy tends temporarily toward a larger radius,

$$\Delta W_i > 0 \Rightarrow \Delta R_i > 0$$

while subsequent energy transfer reduces the local excess and distributes the structural deformation along the coherent chain.

The terminal region responds differently from the interior. Because the last half-waves already possess reduced transverse radii, an additional energy flux reaching the end does not encounter an abrupt boundary. Instead, it strengthens the weakened terminal half-waves.

Thus,

$$R_N \rightarrow R_N + \Delta R_N$$

and field structure can extend into the region beyond the previous effective end of the chain.

The coherent chain therefore grows not by creating an isolated new wave from zero, but by strengthening the smoothly decaying terminal region. The effective end of the electromagnetic structure is displaced outward,

$$L_{\text{coh}} \rightarrow L_{\text{coh}} + \Delta L$$

The newly strengthened terminal region then becomes part of the fully developed coherent structure.

This mechanism can be represented schematically as

reflection → self-overlap
 → local energy excess
 → longitudinal redistribution
 → terminal strengthening → L_{coh}

The process is continuous. No discontinuous creation of a new electromagnetic half-wave is required. The electromagnetic fields evolve smoothly, while the terminal profile of the coherent structure is displaced.

Reflection therefore provides a natural mechanism by which the longitudinal extent of a coherent electromagnetic structure may increase.

For a finite incident wave, the process occurs repeatedly. Successive half-waves reach the mirror and participate in the overlap between the incident and reflected fields. Each interaction produces a new local redistribution of electromagnetic energy. Reflection can therefore generate a sequence of redistribution events rather than a single isolated event.

This sequence may be represented as

$$\Delta W_1, \Delta W_2, \Delta W_3, \dots, \Delta W_N$$

and may be interpreted as a burst of longitudinal energy-redistribution processes travelling through the coherent structure.

As these events reach the terminal region, they may progressively strengthen the previously weakened end of the chain and increase its coherent length.

The total electromagnetic energy must nevertheless remain conserved in an ideal reflection. If the same total energy becomes distributed over a longer coherent structure,

$$W_{\text{tot}} = \text{const}$$

while

$$L_{\text{coh}}$$

the average energy per unit longitudinal length must decrease,

$$\frac{W_{\text{tot}}}{L_{\text{coh}}}$$

Within the geometric model developed in this work, this provides a possible mechanism for a simultaneous reduction of the equilibrium transverse radius,

$$L_{\text{coh}} \uparrow \Rightarrow R_0$$

Thus reflection may produce two complementary structural changes:

$$L_{\text{coh}}$$

and

$$R_0$$

The electromagnetic structure becomes longitudinally longer and transversely narrower.

The present interpretation remains a structural hypothesis of the model. Maxwell's equations govern the smooth local evolution of the electric and magnetic fields and the associated electromagnetic energy flow. The additional assumption introduced here is that a coherent electromagnetic wave consists of mutually coupled half-waves whose stable interior geometry is characterized by R_0 , while the terminal region gradually contracts because of reduced neighbouring support.

Under this assumption, reflection does not merely reverse the direction of propagation. It can also act as a mechanism for redistribution of electromagnetic energy within the coherent structure and for extension of its longitudinal coherence.

11. Quantitative Parameters and Experimental Verification

The preceding chapters developed a geometrical and dynamical interpretation of electromagnetic-wave propagation. The model proposes a continuous transverse field structure, periodic transformation through an intermediate configuration associated with

displacement current, and a possible saturation mechanism regulating the characteristic field amplitudes.

These mechanisms provide a framework for describing the proposed electromagnetic wave. However, a quantitative theory must also determine its characteristic dimensions and field magnitudes.

The present chapter identifies the principal parameters of the model and outlines how their values may be constrained through subsequent theoretical and experimental investigation.

11.1. Characteristic Parameters of the Electromagnetic Wave

The proposed electromagnetic-wave structure is characterized by its longitudinal wavelength, transverse geometry, and electric and magnetic field amplitudes.

The longitudinal wavelength is related to frequency through the conventional vacuum propagation relation:

$$c = \lambda f$$

The characteristic transverse geometry is described by the radius R and effective radial thickness a .

The model additionally introduces hypothetical saturated electric and magnetic amplitudes, E_0 and B_0 .

These quantities describe different properties of the electromagnetic wave. The wavelength determines its longitudinal periodicity, while R and a characterize the spatial distribution of electromagnetic energy around the propagation axis.

The model does not assume that R is universally proportional to the wavelength.

Furthermore, the proposed saturation mechanism allows the equilibrium transverse radius to depend on the energy contained in the wave.

Consequently, determining the characteristic amplitudes does not automatically determine the transverse dimensions.

A complete quantitative description must establish the relationship between these parameters through the actual three-dimensional electromagnetic field distributions.

11.2. Reference Field Amplitudes

The mathematical derivation of the proposed saturated amplitudes remains an open problem.

In particular, the model has not yet established the precise spatial organization of the fields required to produce a dynamically regulated saturated state.

Nevertheless, the subsequent analysis of electromagnetic-wave interaction with a bound electron requires representative field magnitudes.

A provisional reference value for the characteristic electric-field amplitude is

$$E_0 \approx 1.5 \times 10^9 \text{ V/m}$$

For corresponding propagating field components satisfying the approximate relation between their amplitudes, the associated magnetic-field amplitude is

$$B_0 \approx 5 \text{ T}$$

These values are introduced as working parameters for the subsequent investigation.

They are not derived from the saturation mechanism presented in this paper and should not be interpreted as experimentally established universal field amplitudes.

Their significance depends on whether they can consistently account for independent observations without separate adjustment for each experimental case.

11.3. Energy and Transverse Dimensions

Within the approximate geometrical description developed in Section 7, the energy of a saturated electromagnetic-wave region depends on its characteristic transverse radius.

For geometrically similar field profiles at a fixed wavelength, this relationship is represented by

$$W = C\lambda\epsilon_0 E_0^2 R^2$$

Here, C incorporates the effective spatial distribution of electromagnetic energy, including the contribution assigned to the intermediate configuration associated with displacement current.

The expression provides a possible relationship between energy and transverse geometry. It does not independently establish the numerical value of R because the total energy and the complete geometrical coefficient must also be determined.

Furthermore, the relation assumes that the relative field profiles remain approximately similar as the transverse dimensions change.

A more complete electromagnetic field description may require a geometry-dependent coefficient.

The proposed model therefore treats the quantitative determination of R and a as a separate problem from the introduction of characteristic saturated amplitudes.

11.4. Connection to the Interaction with an Electron

The interaction between an electromagnetic wave and a bound electron provides a possible route for investigating the model's characteristic parameters.

An electron responds to the local electric and magnetic fields and to their temporal and spatial variation.

Consequently, the outcome of an interaction may depend not only on the total electromagnetic energy but also on the field

amplitudes, transverse geometry, relative orientation, and available interaction time.

The displacement-current amplitude introduces an additional frequency-dependent quantity:

$$J_{D,0} = \epsilon_0 \omega E_0$$

If the characteristic saturated electric-field amplitude remains approximately constant across different frequencies, the displacement-current amplitude increases with frequency.

This provides a possible connection between the temporal dynamics of the proposed electromagnetic structure and its interaction with matter.

The model therefore suggests that the characteristic field amplitudes and dimensions may be constrained by studying the response of a bound electron to the evolving electromagnetic fields.

However, the existence of such a connection does not by itself establish the photoelectric threshold or the experimentally observed photon-energy relation. These require a quantitative interaction model.

11.5. Quantitative Investigation in Part V

Part VI will extend the present model to the interaction between an electromagnetic wave and a bound electron.

Its objective will be to investigate whether the proposed field configuration can account for the characteristic behavior of the photoelectric effect.

Particular attention will be given to determining or constraining the transverse radius R, effective radial thickness a, and characteristic longitudinal interaction length.

The latter must be distinguished from the wavelength itself. Although the longitudinal electromagnetic periodicity is determined by λ , the spatial interval over which an electron interacts coherently with the field may

depend on the interaction geometry and dynamics.

The subsequent analysis will also examine whether a common set of characteristic field amplitudes can describe interactions at different frequencies and for different bound-electron states.

The representative values introduced in Section 10.2 provide an initial basis for this investigation.

Their consistency must ultimately be evaluated against experimental observations.

A quantitative agreement obtained for a single threshold would not be sufficient to establish the proposed saturation mechanism. A more discriminating test requires the same parameters to describe several independent observations.

11.6. Experimental Significance and Further Development

The principal quantitative challenge of the present model is to establish the proposed electromagnetic structure without introducing independently adjustable parameters for every experimental situation.

A successful description would need to determine the characteristic field amplitudes, transverse geometry, and energy redistribution from a consistent electromagnetic framework.

The present paper does not complete that task.

Instead, it identifies the structural hypotheses and the parameters whose values must be established.

The proposed interaction with a bound electron provides one possible route for testing these assumptions, while a complete three-dimensional field solution remains necessary to determine the underlying saturation mechanism.

Part VI therefore represents the next stage of the investigation: moving from the proposed structure and propagation of the

electromagnetic wave toward quantitative constraints obtained from its interaction with matter.

The following chapter summarizes the remaining theoretical questions and the principal requirements for developing the model into a complete electromagnetic description.

12. Discussion and Open Problems

The present paper develops a conceptual physical picture of an electromagnetic wave as a continuous, periodically evolving three-dimensional field structure. Its principal elements are an approximately annular organization of the electric and magnetic fields, an intermediate electromagnetic configuration associated with Maxwell's displacement current, continuous redistribution of electromagnetic energy, and a possible dynamical regulation of the transverse geometry.

The purpose of Part IV is not to complete every quantitative aspect of this model. Rather, it establishes the geometrical and dynamical framework from which the subsequent developments follow.

Several questions introduced here are therefore not left unresolved within the complete series. Part V develops the structural evolution of the electromagnetic wave, including saturation, energy-dependent transverse dimensions, coherent merging, growth of the characteristic transverse radius R_0 , and changes of wave energy during propagation. Part VI examines the local interaction with bound electrons and uses the photoelectric effect to constrain characteristic field amplitudes and interaction dimensions.

The remaining open problems are more fundamental. They concern whether the proposed physical picture can ultimately be

derived from a complete electromagnetic field solution.

12.1. Complete Three-Dimensional Field Solution

The principal theoretical problem is the construction of explicit three-dimensional electric and magnetic fields that reproduce the proposed wave structure.

Such fields must satisfy the complete Maxwell equations, including the divergence conditions, Faraday's law, and the Ampère-Maxwell equation. They must also reproduce longitudinal propagation while remaining consistent with local conservation of electromagnetic energy and momentum.

The annular and intermediate configurations introduced in this paper are presently geometrical and dynamical descriptions. A complete solution must determine their actual vector fields, radial profiles, longitudinal dependence, and temporal evolution.

The decisive question is therefore whether the proposed continuously evolving structure can exist as a self-consistent electromagnetic field configuration without requiring an external confining mechanism.

12.2. Intermediate Electromagnetic Configuration

The quarter-period relationship between a sinusoidally varying electric field and displacement current follows directly from Maxwell's equations. The interpretation of this relationship as a periodic transformation through a distinct intermediate spatial configuration is an additional structural hypothesis.

The model proposes that this configuration provides continuity between successive phases of the electromagnetic wave and participates in redistribution of electromagnetic energy.

In particular, the complementary energy assigned to the intermediate configuration must ultimately be represented entirely

through the complete electromagnetic fields. It must not constitute an additional independent form of energy.

A quantitative solution must therefore demonstrate how the intermediate configuration participates simultaneously in field evolution, energy conservation, and longitudinal energy transport.

12.3. Electromagnetic Momentum and Radial Stability

The proposed transverse regulation is based on the possibility that small differences between the spatial distributions of the electric and magnetic fields influence radial electromagnetic energy and momentum transport.

Within the conceptual model, an undersaturated structure tends to contract, an oversaturated structure tends to expand, and a saturated structure approaches radial equilibrium.

The direction of the corresponding radial Poynting-vector component provides an indication of energy redistribution, but energy flow alone does not establish the mechanical stability of the electromagnetic structure.

A complete treatment must therefore evaluate the electromagnetic momentum balance, including the Maxwell stress tensor.

The fundamental remaining question is whether the proposed field geometry produces a restoring response around the saturated configuration.

12.4. Magnetic Closure and Periodic Transformation

The absence of magnetic monopoles is compatible with closed magnetic-field configurations, but it does not uniquely determine the annular geometry proposed in this model.

A complete field solution must establish whether the required magnetic organization

can remain continuous while the electromagnetic wave passes through its successive phases.

The transformation between the annular and intermediate configurations must preserve both field continuity and electromagnetic energy and momentum.

The possible role of phase closure and magnetic geometry in constraining the internal structure therefore remains an important theoretical problem.

12.5. Parameters Developed in Part V

Part IV introduces the concept that electromagnetic waves with different energies may possess different transverse dimensions while approaching similar saturated field amplitudes.

The detailed evolution of this transverse structure is developed further in Part V.

In particular, Part V examines the relationship

$$R_0 = R_0(W),$$

the increase of transverse size with wave energy,

$$\frac{dR_0}{dW} > 0,$$

the coherent merging of electromagnetic waves, and the growth or reduction of W and R_0 during propagation.

The quantitative form of the function $R_0(W)$ remains subject to further refinement, but the question of structural evolution is therefore treated as a continuation of the present conceptual framework rather than as an unresolved problem confined to Part IV.

12.6. Parameters Constrained in Part VI

Part IV also introduces characteristic field amplitudes E_0 and B_0 without deriving their numerical values from the internal field dynamics.

Part VI approaches this problem from the opposite direction. Instead of deriving the amplitudes entirely from the free electromagnetic wave, it examines their consequences during interaction with a bound electron.

The photoelectric effect provides constraints on the characteristic field amplitudes, local interaction dimensions, and the amount of energy transferred during an electron-ejection event.

This establishes an important distinction between two complementary tasks:

$$\text{field dynamics} \rightarrow E_0, B_0$$

and

$$\begin{aligned} &\text{interaction with matter} \\ &\rightarrow \text{constraints on } E_0, B_0. \end{aligned}$$

Agreement between these two routes would provide a substantially stronger test of the model than either approach alone.

12.7. Experimental Verification

The proposed model should ultimately be tested through observations that distinguish its structural predictions from a description based only on conventional wave parameters.

Part V identifies possible tests associated with transverse coherence, coherent merging, structural growth, and the characteristic transverse radius R_0 .

Part VI provides a separate experimental route through interaction with bound electrons and the photoelectric effect.

These later investigations do not remove the need for a complete field solution. They provide independent empirical constraints that such a solution must satisfy.

The strongest development of the model would therefore combine three requirements:

$$\begin{aligned} &\text{Maxwell-consistent field structure,} \\ &\text{"\{stable transverse dynamics\},} \end{aligned}$$

and

agreement with interaction experiments.

The purpose of Part IV is to establish the common physical framework within which these requirements can be investigated.

13. Conclusions

This paper introduces a conceptual three-dimensional interpretation of an electromagnetic wave as a continuous, periodically evolving physical structure.

The proposed electromagnetic wave is not treated as a succession of independent objects. Successive half-wavelength regions represent different phases of one connected electromagnetic process whose internal field organization changes continuously during propagation.

The model considers an approximately annular transverse organization of the electric and magnetic fields and assigns an important role to Maxwell's displacement current. The quarter-period relationship between a varying electric field and displacement current provides the temporal basis for a proposed intermediate electromagnetic configuration connecting successive phases of the wave.

This intermediate configuration is not interpreted as an additional independent form of energy. It represents a complementary organization of the electromagnetic field through which continuity and energy redistribution may be maintained.

A second central element of the model is the possible dynamical regulation of transverse geometry. Differences between the spatial distributions of the electric and magnetic fields are proposed to influence radial electromagnetic energy and momentum transport. This leads to the conceptual distinction between undersaturated, saturated, and oversaturated wave structures.

In the proposed saturated state, characteristic field amplitudes may remain approximately stable while the transverse dimensions depend on the total energy contained in the electromagnetic structure. The model therefore separates longitudinal periodicity, determined by wavelength, from transverse size, which may evolve independently with wave energy.

Part IV establishes this geometrical and dynamical foundation.

Part V continues the development by examining how electromagnetic-wave structures evolve during propagation. It considers saturation, coherent merging, energy-dependent transverse size, growth of R_0 , fragmentation, and changes of wave energy caused by interactions and external fields.

Part VI then examines the local interaction of these structures with bound electrons. The photoelectric effect provides a route for constraining the characteristic field amplitudes and local interaction geometry and for distinguishing the total energy of an electromagnetic wave from the energy transferred in an individual electron-ejection event.

The three parts therefore address successive levels of the same model:

Part IV: physical structure of the EM wave

Part V: *evolution and growth of the EM – wave structure*

Part VI: *local interaction of the EM wave with matter*

The principal unresolved theoretical requirement is now more sharply defined. A complete three-dimensional electromagnetic field solution must reproduce the proposed geometry, periodic transformation, energy transport, and transverse stability while satisfying Maxwell's equations and the full electromagnetic momentum balance.

Part IV therefore serves not as the final quantitative description of the electromagnetic wave, but as the conceptual foundation on which the subsequent structural and interaction-based analysis is built.