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The theory of unbound modes on circular dielectric waveguides

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The electromagnetic field propagating along an ideal dielectric waveguide may contain both bound and unbound (radiation) components. In a transverse spectral representation, the bound field is represented by a finite sum of discrete modes but the unbound field requires integration over a continuum of modes. This integration, while it provides an exact description of the radiation field, can be very slowly convergent. An asymptotic representation using improper (leaky) modes is more rapidly convergent but is only valid in a restricted region of space.

The purpose of this thesis is to study both the spectral and improper unbound modes, and the connection between them.

Chapter 1 provides some general background to the modal theory of electromagnetic-field propagation in dielectric waveguides, with particular emphasis on the unbound modes. It defines the physical system to be studied and the basic notation to be used in the remainder of the thesis and, along the way, re-derives some well-known results of electromagnetic theory for later use.

In Chapter 2, the bound modes of a circular dielectric rod are listed, and the spectral radiation modes derived, in a form found most useful for later analysis. Orthogonality and normalization conditions for the radiation modes are derived using a general formalism which yields a relationship between free-space and modal fields valid in a much wider class of systems than those of specific interest here.

These orthonormality conditions are used in Chapter 3 to study the

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excitation and propagation of the radiation modes within a circular dielectric rod. The first source used is a truncated plane wave. The effects of changing the angle of incidence or the extent of the source field are studied. A close analogy is found between the far-field radiation pattern of a dielectric waveguide with small dielectric-constant-difference between core and cladding and the diffraction pattern of a circular aperture. Similar calculations are then repeated with a quasi-monochromatic, totally incoherent source.

In Chapter 4, the transformation is made from the transverse spectral representation of the waveguide field to a longitudinal representation. A steepest-descent approximation is then made by which the integral over the continuum of radiation modes is replaced, within a restricted region, by a sum over discrete, improper, unbound modes - leaky modes - plus a saddle-point contribution. The leaky modes are shown to be the analytic continuation of bound modes below cutoff and the range of significance of the saddle-point term is estimated. Two methods for determining the orthogonality and excitation of leaky modes are investigated.

The detailed characteristics of leaky modes are studied, both numerically and asymptotically in Chapter 5. Using these characteristics, the excitation and propagation of the radiation field are studied in terms of leaky modes under the same excitation conditions as used in Chapter 3. These results are used to estimate the range of validity of the leaky ray theory. The number of leaky modes with a given attenuation and the effect on this attenuation of including material absorption are also discussed.

In Chapter 6, some of the above ideas are applied to the optical waveguides in visual photoreceptors. The contribution of unbound modes to light absorption in these structures is investigated and an ambiguity in the method of determining photoreceptor parameters by observation of mode cutoffs is pointed out.

The major conclusions of the thesis are summarized in Chapter 7.