Fiber design—from optical mode to index profile

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Abstract. Designing fibers with a certain modal profile may lead to improved performance. We demonstrate that it is possible to derive the index profile from the desired modal characteristics. Along with an efficient beam propagation code, the procedure may expedite the development of special fibers. [DOI: 10.1117/1.1555735]

Subject terms: optical fibers; optical fiber theory; beam propagation.

Paper 020299 received Jul. 8, 2002; revised manuscript received Oct. 3, 2002; accepted for publication Oct. 4, 2002.

1 Introduction

Recently, the customization of fiber designs has become increasingly important. For example, in the dense wavelength-division multiplexing systems, hundreds of channels at different wavelengths propagate in one fiber. Boosted by the Er-doped fiber amplifiers, signals can transmit over a very long distance without requiring electronic regeneration. In such systems, the optical nonlinearity can limit the performance.[1,2] To alleviate the problem, fibers with a large effective area are developed.[3–5] There are many applications that can benefit from custom-mode patterns. For example, fibers with an apodized mode can offer high uniformity in intensity for industrial and medical applications. In designing new fibers, the index profile is the key.[6] Designs derived from experiences are verified through the fabrication and testing cycles or through numerical simulations.

Many methods were developed in the past to simulate optical waveguides. Among them is the effective index method, which reduces a channel waveguide to a easily solvable planar waveguide.[7,8] Since fast computers are readily available, computationally intensive codes, such as the beam propagation method (BPM), have been established for simulations of waveguides.[9,10] The original BPM uses the paraxial, scalar-field approximations. Many BPM codes, including, the finite-difference, semivectorial, vectorial, and large-angle analyses, have been developed.[11–18] In BPM calculations, the index profile is used as the input. From the index profile, the modal characteristics are obtained. There are reports on running BPM in the cylindrical coordinate system.[19–21] Most of them deal with the bending loss. However, to our knowledge, there has been no prior effort to derive the index profile from the modal profile, probably because the loss and dispersion are considered to be more crucial.

In this paper, we demonstrate that one can derive the index profile from the desired modal characteristics. We also present the finite-difference beam propagation code in the cylindrical coordinate system. This procedure may expedite the development of new fibers.

2 Formalism

The Helmholtz equation of the E field is given by

$$\nabla^2\mathbf{E}+k_0^2n^2\mathbf{E}-\nabla(\nabla\cdot\mathbf{E})=0, \tag{1}$$

where k_0 is the magnitude of the wave vector, and n is the index profile of the waveguide. For a linearly polarized mode in a cylindrical fiber, Eq. (1) becomes

$$\frac{\partial}{\partial r}\left(\frac{1}{\epsilon}\frac{\partial\epsilon E}{\partial r}\right)+\frac{1}{r}\frac{\partial E}{\partial r}-\frac{l^2}{r^2}E+k_0^2(n^2-n_{\mathrm{eff}}^2)E=0, \tag{2}$$

where ϵ is the dielectric constant, and n_{eff} is the effective index of the mode. The angular dependence of the E field is assumed to be $\exp(il\theta)$. When the difference between indices of the core and the cladding is small, the field and its derivative are continuous across the dielectric interface. In the scalar-field approximation, the ϵ terms in Eq. (2) cancel, facilitating the derivation of index profile from the effective index of the mode and the modal profile.

From the modal profile and the effective index, a unique index profile can be calculated. If only the modal profile is of concern, one can find different index profiles supporting the same modal profile by using the effective index as an adjustable parameter. However, the choice of the effective index is not completely arbitrary. Since the index change in a fiber is limited, an arbitrarily chosen effective index may not lead to an experimentally realizable fiber.

We use the finite-difference discretization in solving Eq. (2) and in conducting the BPM:

$$E(z+\Delta z)=\frac{2ik_0n_r+L\Delta z/2}{2ik_0n_r-L\Delta z/2}E(z), \tag{3}$$

$$LE_i=a_iE_{i-1}-b_iE_i+c_iE_{i+1}, \tag{4}$$

$$a_i=\frac{2n_{i-1}^2}{n_i^2+n_{i-1}^2}\cdot\frac{1}{\Delta r^2}-\frac{1}{2r_i\Delta r}, \tag{5}$$

$$b_i = 2n_i^2\left(\frac{1}{n_i^2+n_{i-1}^2}+\frac{1}{n_i^2+n_{i+1}^2}\right)\times\frac{1}{\Delta r^2}-k_0^2(n_i^2-n_r^2)+\frac{l^2}{r_i^2}, \quad (6)$$

$$c_i = \frac{2n_{i+1}^2}{n_i^2+n_{i+1}^2}\cdot\frac{1}{\Delta r^2}+\frac{1}{2r_i\Delta r}, \quad (7)$$

where n_r is the reference index. By focusing on one l value at a time, it is very efficient to run the 1-D BPM code. In our simulations, we use a 160 μm calculation window discretized into 1600 grid points. To avoid singularity at $r=0$, the center of the fiber is located in between two grids. The efficiency of the code can be improved by implementing the absorbing boundary condition. Since the run time of the current code on a personal computer is only a few seconds, the efficiency is not a concern at this time.

High accuracy is required to calculate the group velocity dispersion and the effective mode area. This is achieved by using the iterative BPM. Initially, a Gaussian beam is launched into the waveguide, as in the conventional BPM, to obtain the approximate modal profile and index. The modal profile obtained is relaunched to obtain modal properties with high accuracy. To find the wavelength dependence, the finite-difference BPM is carried out repetitively for a series of wavelengths.

The BPM code can handle both the single-mode and multimode fibers. In the case of multimode fibers, LP modes corresponding to the same order of the Bessel function are obtained by the simulation code together as a group. In this paper, we focus on the single-mode fiber.

3 Results

To evaluate the BPM code in the cylindrical coordinate system, we simulate the fundamental mode of a well-established[22] step-index fiber, namely, Corning SMF-28, with a core diameter of 8.2 μm. The cladding index is that of the pure silica and the core index is increased[23] by 0.36%. The calculated mode field diameter at 1550 nm is 9.8 μm, while the specification is 10.4 ± 0.8 μm. We also simulate a dispersion-shifted fiber with a triangular index profile in the core region.[24] The index at the center of the core is increased by 1.1%. The full diameter of the core is 6.2 μm. The raised outer ring is located between 4 and 5.5 μm with an increase in index of 0.2%. Results of the directly calculated group velocity dispersion, which is much more sensitive to the accuracy of the simulation code than the modal profile, are shown in Fig. 1. They match well with the published results. For SMF-28, the specification of the zero-dispersion wavelength is $1302\ \text{nm}\leqslant\lambda_0\leqslant 1322$ nm.

To verify that the index profile can be derived from the mode pattern, we consider a classical, closed-form E field:

$$E(r)=\begin{cases} 0.5\cdot\left[1+\cos\left(\frac{\pi}{2}\cdot\frac{r}{a}\right)\right], & r\leqslant a \\ 0.5\cdot\exp[-\pi(r-a)/2a], & r>a. \end{cases} \quad (8)$$

The boundary between the cosine function and the exponential function is located at $a=5$ μm. At the boundary, the field is at half maximum and the slope of the E field is continuous. The effective index of the mode is assumed to be 1.45. The E field and the derived index profile are shown in Fig. 2. Applying the BPM to the index profile, we confirm that the E field calculated by the BPM from the derived index profile is indistinguishable from the original E field. The index in the core and the cladding is not uniform due to the second term in Eq. (2).

Among a variety of numerical designs explored, the following design provides an apodized mode. The E field is shown in Fig. 3 along with the index profile. The effective index of the mode is 1.453 and the effective mode area is 75.5 μm^2 (Ref. 2) at 1.55 μm (Ref. 5). It is a single-mode

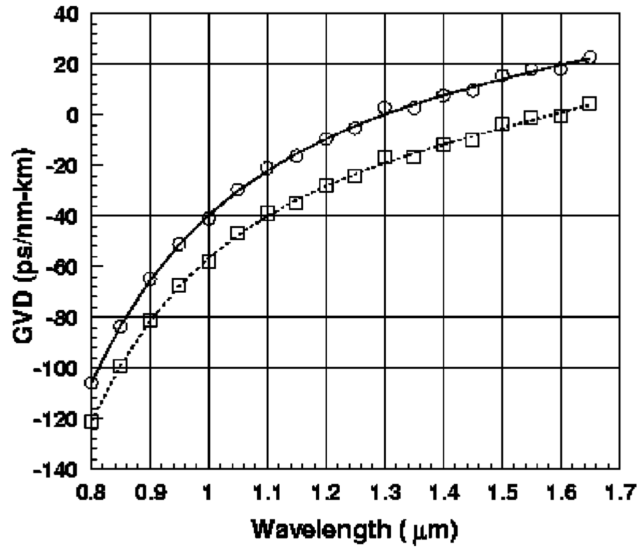

Fig. 1 Group velocity dispersion of a step-index fiber shown as the solid curve and a dispersion-shifted fiber shown as the dotted curve. Calculated data points are also shown.

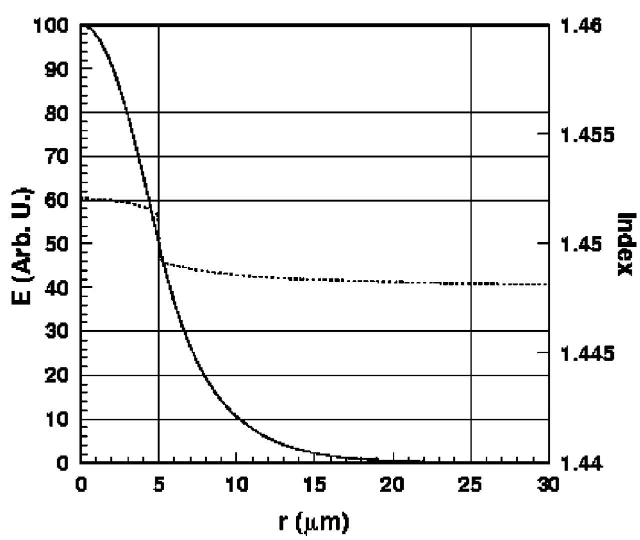

Fig. 2 Mode profile, i.e., E field, defined by Eq. (8) and the index profile derived from the modal characteristics. The solid curve is the E field with the peak normalized to 100% and the dotted curve is the index profile.

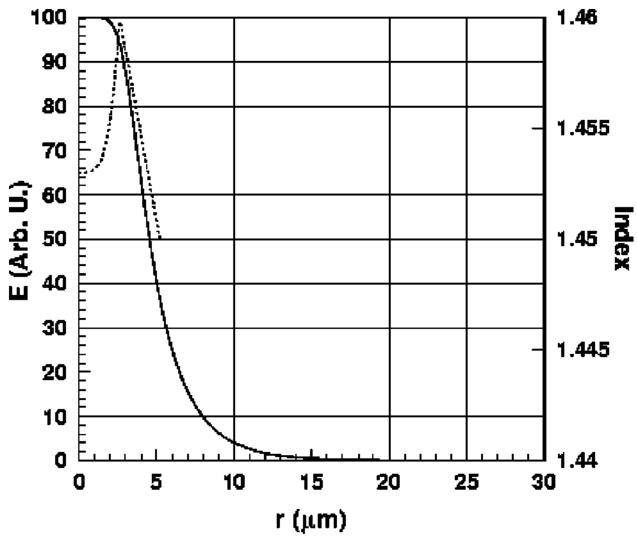

Fig. 3 Profile of an apodized fundamental mode, shown as the solid curve, with an effective mode area of 75.5 μm^2 at the wavelength of 1.55 μm and the corresponding index profile, shown as the dotted curve.

guide with a core diameter of 9.6 μm. From numerical simulations, we conclude that to obtain an apodized mode, the index profile should have a large radius of curvature, i.e., nearly flat, at the center. The index at the center should also match the effective index of the mode.

It is interesting to examine the index profile required to support a tightly confined mode for the near-field scanning optical microscope.[25] To guide a mode similar to what is shown in Fig. 1 but with a full width at half maximum of 40 nm at the wavelength of 488 nm, one would require a difference in dielectric constants between the core and cladding of 73.4. Although there is no material system with such a large difference in dielectric constants at the present time, deriving the index profile from modal characteristics provides a direction for future exploration. The current procedure is also limited to the mode profile. For long-haul transmission, the group velocity dispersion plays a very important role. It is yet to be explored whether it is possible to derive the self-consistent index profile from the desired group velocity dispersion.

4 Conclusion

We presented a BPM code in the cylindrical coordinate system that is very efficient for determining modal properties of fibers. By examining the inverse problem, we also demonstrated that it is possible to derive the index profile from specific modal characteristics. The procedure is applicable to waveguides with a small index difference. A design yielding apodized mode profile was presented. Such a procedure can expedite the development of special fibers.

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