

Engineering modes in optical fibers with metamaterial

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Abstract In this paper, we report a preliminary theoretical study on optical fibers with fine material inclusions whose geometrical inhomogeneity is almost indistinguishable by the operating wavelength. We refer to such fibers as metamaterial optical fibers, which can conceptually be considered as an extension from the previously much publicized microstructured optical fibers. Metamaterials can have optical properties not obtainable in naturally existing materials, including artificial anisotropy as well as graded material properties. Therefore, incorporation of metamaterial in optical fiber designs can produce a new range of fiber properties. With a particular example, we will show how mode discrimination can be achieved in a multimode Bragg fiber with the help of metamaterial. We also look into the mean field theory as well as Maxwell-Garnett theory for homogenizing a fine metamaterial structure to a homogeneous one. The accuracies of the two homogenization approaches are compared with full-structure calculation.

Keywords optical fiber, metamaterial, Bragg fiber, mode discrimination

1 Introduction

A metamaterial is a composite that is structurally (rather than chemically) formed by two or more element materials. The structural feature size is normally kept at a subwavelength scale, so the composite material appears to the operating wavelength as a homogenized material. The holey air-silica cladding of the recently much publicized microstructured optical fiber (MSOF) can, in fact, be considered as a special type of metamaterial. The emerging metamaterial technology was mostly motivated by the possibility of producing an artificial material with

negative permittivity or/and negative permeability. For such purposes, metal inclusions are usually necessary [1,2]. However, in a broader sense, metamaterial encompasses all structured materials that have electromagnetic (EM) response not attainable by each individual composing material. Particularly for low-loss waveguiding applications, metal inclusion is, in general, not desired because of its relatively high absorption loss. Furthermore, because of the special fiber drawing technology, the metamaterial types that can be incorporated in this context are limited. The primary restriction is that the fiber structure should at least be translationally invariant in the fiber axial direction. Here, we will confine our discussions to all-dielectric metamaterials, whose structural inhomogeneity is only in the fiber cross-section domain. We refer to such a fiber as metamaterial optical fiber (MMOF).

Incorporation of metamaterials can facilitate fiber designs with interesting properties beyond what can be achieved in conventional step-index fibers or even in MSOFs. In general, deployment of metamaterials can be used for the following purposes: a) mode discrimination, b) dispersion engineering, c) birefringence control, and d) nonlinearity tailoring. As a particular example, we will present how the modes in the second-order group in a multimode Bragg fiber can be separated in their dispersion curves. Such a fiber is advantageous if one favors a particular mode over others. Such a design can also be used for reduction of intermodal cross talk in multimode fibers.

Owing to the metamaterial's subwavelength nature, it has been a common theoretical practice to replace the fine structure of metamaterial to a homogenized material with effective permittivity and permeability tensor distributions. In previous MSOF studies (especially for index-guiding type), the so-called effective index method has been proposed to simplify otherwise tedious numerical calculations [3–5]. In such an approach, the propagation constants of the fundamental space-filling mode (FSM), β_{FSM} , is used to derive the effective index (n_{FSM}) of the cladding composite. An isotropic cladding with index at n_{FSM} is then used to replace the holey cladding. Another existing

homogenization approach is by using the well-known Maxwell-Garnett theory to reduce a subwavelength structure to a homogenized material, usually characterized by an effective permittivity tensor. Here, we will deploy both methods to derive mode properties of an MMOF. The accuracies of two approaches will be compared with results calculated using its full structure.

2 Previous study and fiber structures

First, we briefly summarize previous related theoretical and experimental efforts in this particular field. There have been a huge number of research publications on MSOFs. However, most of them emphasize the role of composite cladding. Of course, the photonic bandgap (PBG) possessed by some air-silica cladding structures promises novel hollow waveguiding. However, for other purposes such as mode discrimination, dispersion engineering, and birefringence control, using a composite core can sometimes be an equally compelling approach as compared with using a composite cladding. Especially, waveguide modes are largely confined in the core region. The high-field overlapping ratio suggests that the core material should affect properties of the modes more heavily. Some previous theoretical and experimental studies deploying a composite core mostly focus on the birefringence property of an optical fiber. An index-guiding fiber with a one-dimensional (1D) layered core is reported in Ref. [6], whose cross-section is schematically shown in Fig. 1(a). By introducing asymmetry to the fiber structure, the degeneracy of the two otherwise degenerate fundamental modes is lifted. High birefringence can therefore be achieved. Another similar work was shown in Ref. [7,8], whereby an array of elliptical rods are included in the fiber core structure to achieve high-fiber birefringence. A corresponding schematic diagram is shown in Fig. 1(b). Compared with the fiber illustrated in Fig. 1(a), the new design is considered more practical, because one can start from circular rods (which is a commercially ready product)

plus proper fiber-drawing technique to obtain the final fiber structure. As no polishing is involved for forming the preform (which is necessary for fabricating the fiber shown in Fig. 1(a) [6]), loss is expected to be small. A proof-of-concept experimental demonstration is recently reported in Ref. [9], where a fiber with a core formed by an array of circular germanium-doped rods is fabricated. Despite the complex core structure, propagation loss as low as 3.5 dB/km has been obtained at 1550-nm wavelength.

Besides birefringent optical fiber designs, another potential application of metamaterial inclusion is mode selection in multimode fibers. In certain applications, for example, optical tweezing, hollow beam with azimuthal or radial polarization is of very high interest. The modes corresponding to such a hollow beam in a standard step-index optical fiber belong to some high-order mode group, and they always nearly degenerate to some other modes. Nanostructured metamaterial can be deployed to effectively discriminate the modes with close propagation constants. Here, we will show in particular how the first transverse electric mode (TE_{01}) and the first transverse magnetic mode (TM_{01}) can be separated in their dispersion curves in a multimode fiber by using a cylindrically arranged multilayered metamaterial. Although the cylindrically structured core can be applied to conventional step-index fiber design, here, we choose a Bragg fiber system. The property of wavelength-dependent radiation loss possessed by Bragg fibers would provide us some extra information for judging the accuracies of theoretical models. We envisage that similar design can effectively avoid modal mixing problems in a structurally perturbed Bragg fiber [10]. A conventional Bragg fiber is illustrated in Fig. 2(a), where a periodic cladding is used to achieve frequency-dependent wave guidance through the PBG effect. In Fig. 2(b), a structured metamaterial made of concentric cylindrical layers is used to replace the previously homogeneous core, whereas in Fig. 2(c), the inhomogeneity of the core metamaterial is along the azimuthal direction. The modal properties of the fiber in Fig. 2(b) will be studied in detail in the following section.

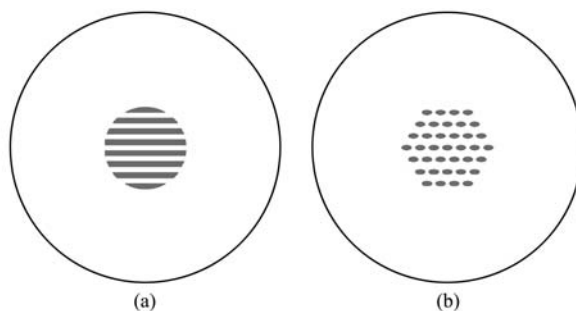


Fig. 1 Schematic diagrams of metamaterial optical fibers with high birefringence. (a) Fiber with core made of 1D layered medium; (b) fiber with core made of two-dimensional (2D) nanostructured medium (gray region denotes material with higher refractive index than background)

3 Bragg fiber example

First, we study the properties of a conventional Bragg fiber, as shown in Fig. 2(a). The fiber under study is made of two materials at refractive indices $n_1 = 1.5$ and $n_2 = 1.45$. Both indices are achievable by silica with the help of doping. The geometrical parameters of the fiber include core radius $r_{\text{core}} = 15 \mu\text{m}$, high-index cladding layer thickness $d_1 = 1 \mu\text{m}$, and low-index cladding layer thickness $d_2 = 3 \mu\text{m}$. The cladding has four periods of bilayers, followed by a background at index n_1 . The dispersion and loss curves of the second-order modes (TM_{01} , TE_{01} , and the second mixed-polarization mode MP_{21}) are shown in Fig. 3. Mode derivation is done by using the analytical transfer matrix method (TMM) [10–12]. The dispersion curves as well as the loss curves agree perfectly with the projected bandgap of the cladding structure (gray-shaded region in the background), derived using the plane-wave expansion

method. It is noticed from Fig. 3(a) that the three second-order modes are hardly distinguishable in their dispersion curves. Effectively, this suggests that it would be very difficult for us to select one of the modes, for example, by using a fiber Bragg grating or long-period fiber grating. However, the TE_{01} and TM_{01} modes are of special practical interest because of their unique polarization characteristics. Here, we propose a way to separate the dispersion curves of these two modes by introducing a metamaterial core. The modified Bragg fiber is shown by its radial index profile in Fig. 4. The cladding is unchanged compared with the previous case, except that the core is now made of a nanostructured layered metamaterial. The core material is composed of two materials with indices $n_2 = 1.45$ and $n_3 = 1.475$. The period for the core structure is at 400 nm, of which, the layer with higher index has a width of 160 nm. Because of the fact that there are a large number of concentric layers, our TMM code is not well

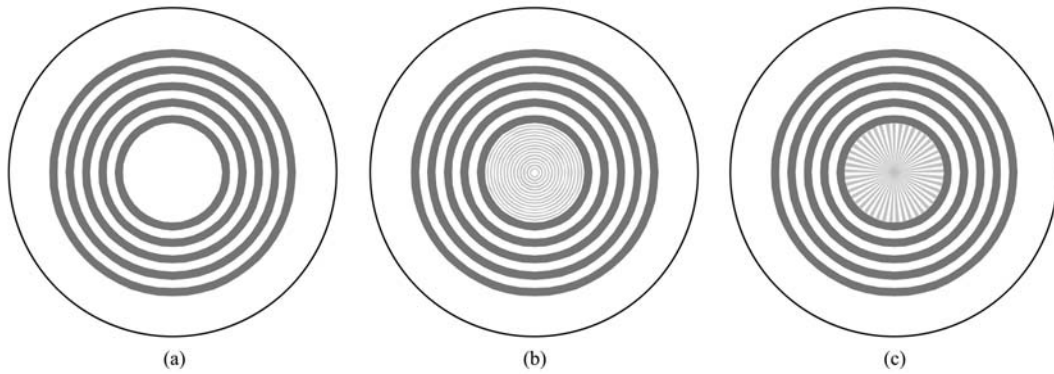


Fig. 2 Schematic diagrams of three Bragg fiber cross-sections. (a) Conventional Bragg fiber with a homogeneous isotropic core; (b) Bragg fiber with a metamaterial core, which is made of subwavelength concentric bilayers; (c) Bragg fiber with a metamaterial core, which is made of subwavelength annular sectors (gray region denotes material with higher refractive index than background)

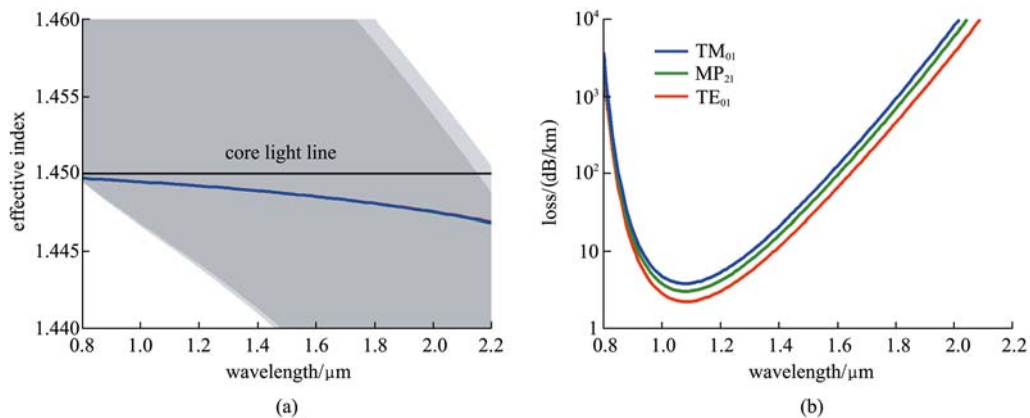


Fig. 3 Dispersion (a) and loss (b) curves of second-order modes in a homogeneous-core Bragg fiber (notice the almost complete overlap of dispersion curves in (a))

behaved because of the near-singular matrix problem. Therefore, we use instead the finite element method (FEM) for all following mode derivations. Our numerical tests for the previous homogeneous-core Bragg fiber reveal that the numerical results can agree almost perfectly with the analytically deduced ones. The numerically derived effective mode index (n_{eff}) can be accurate up to the 9th decimal point.

In Fig. 5, we show the dispersion and loss curves of the TE_{01} and TM_{01} modes in the metamaterial-core Bragg fiber, derived by full-wave FEM calculations. We have focused on the longer wavelengths within the bandgap because of the fact that numerical convergence is much easier to be achieved there. From Fig. 5(a), it is apparent that the two modes are well distinguished in dispersion curves. The losses of the two modes (Fig. 5(b)), in general, get much smaller as compared with the case in Fig. 3. This is because the core now has a larger effective index owing to incorporation of n_3 material. This is also manifested in Fig. 5(a) wherein the dispersion curves are lifted to higher values. The difference in n_{eff} values between the two modes is almost constant, valued around 0.0002. Such a difference is usually sufficient for mode discrimination by

using, for example, the long-period fiber grating technique. It should be noted that the design presented in this paper is not subject to optimization. We envision that such a design methodology would allow many novel fiber structures to be developed for various application purposes.

4 Comparison of homogenization models

Direct calculation of an optical device made of metamaterial is always a demanding numerical task if an analytical solution is not applicable. This difficulty is inherent because of the subwavelength nature of metamaterials. It has been a common theoretical practice to approximate a metamaterial composite with a homogenized one. The homogenized material discards all fine structural features of a metamaterial but retains its macroscopic EM response.

In the MSOF community, especially when dealing with solid-core MSOFs, the concept of space-filling mode is often deployed to simplify the complex holey cladding [3–5]. In such a case, 2D holey cladding is simplified to a homogeneous isotropic material, characterized by a scalar refractive index n_{FSM} . Here, we similarly calculate the

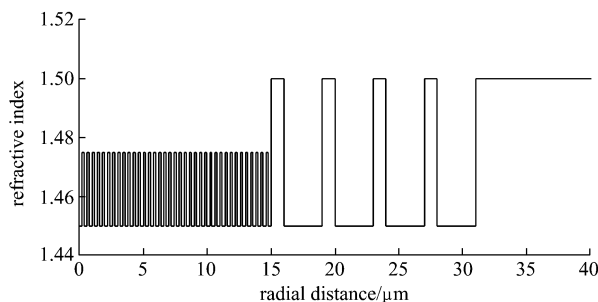


Fig. 4 Index profile along radial position for metamaterial-core Bragg fiber

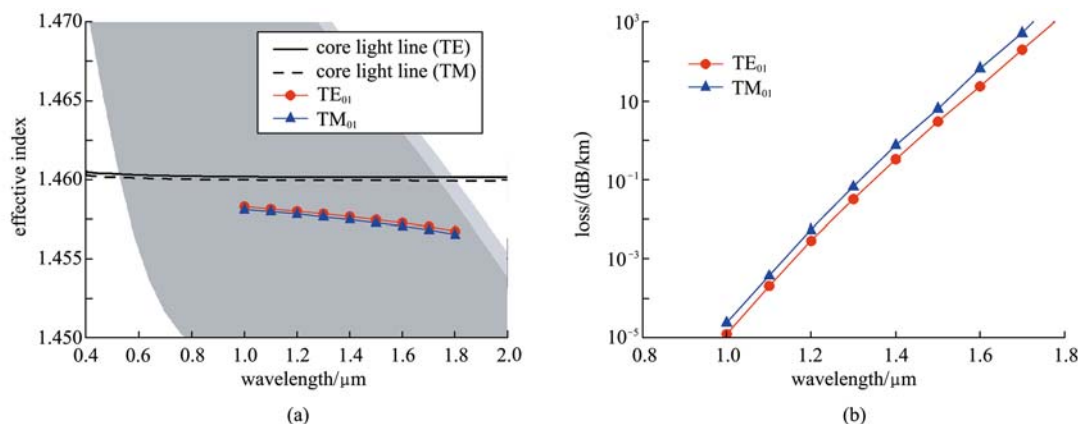


Fig. 5 Dispersion (a) and loss (b) curves of TE_{01} and TM_{01} modes in a metamaterial-core Bragg fiber

FSM of the core material. However, because of the particular layered structure, the FSM is rather computed twice for TE and TM polarizations separately (also shown in Fig. 5(a)). Consequently, the effective index of the TE (TM) FSM mode is used as the refractive index of a homogeneous-core fiber for calculating the guided TE₀₁ (TM₀₁) mode. For convenience, we refer to this approach as mean field theory (MFT).

Another well-known approach to homogenize a metamaterial is to deploy the Maxwell-Garnett theory (MGT). In MGT, the effective permittivity tensor of the layered medium under discussion can be written as

$$\boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_r & 0 & 0 \\ 0 & \varepsilon_\theta & 0 \\ 0 & 0 & \varepsilon_z \end{bmatrix},$$

with

$$\varepsilon_r = f_1 \varepsilon_1 + f_2 \varepsilon_2$$

and

$$\varepsilon_\theta = \varepsilon_z = \frac{\varepsilon_1 \varepsilon_2}{f_1 \varepsilon_2 + f_2 \varepsilon_1},$$

where ε_1 and ε_2 are permittivity values of two element materials and f_1 and f_2 are their corresponding filling fractions fulfilling $f_1 + f_2 = 1$. A homogenized core material characterized by an anisotropic permittivity value can then be used to replace the layered core material for much easier mode derivation.

Using both MFT and MGT homogenization approaches, we rederived the modal properties of the TE₀₁ and TM₀₁ modes (notice that MFT does not apply for deriving the MP₂₁ mode). The n_{eff} and loss values derived by the two approximate methods are then compared with the values obtained by using the full structure (Fig. 5). The relative errors in n_{eff} and loss values for these two methods are plotted in Fig. 6. Figure 6(a) tells that the relative error in n_{eff} for both two methods and for both TE₀₁ and TM₀₁ modes are kept below 0.1%. MGT shows better accuracy than the MFT, which is, however, only at an advantage of about 0.01%. Close to the upper bandgap edge, both models show the tendency of better accuracy. In contrast, Fig. 6(b) shows that the relative error in derived loss value for both MFT and MGT models grows monotonically with the wavelength, from negative to positive. Again, in general, MGT has relatively better accuracy than MFT. The overall error for both homogenization methods are well within one order.

5 Conclusion

In conclusion, we have proposed that incorporation of structured metamaterial in optical fiber design can offer a

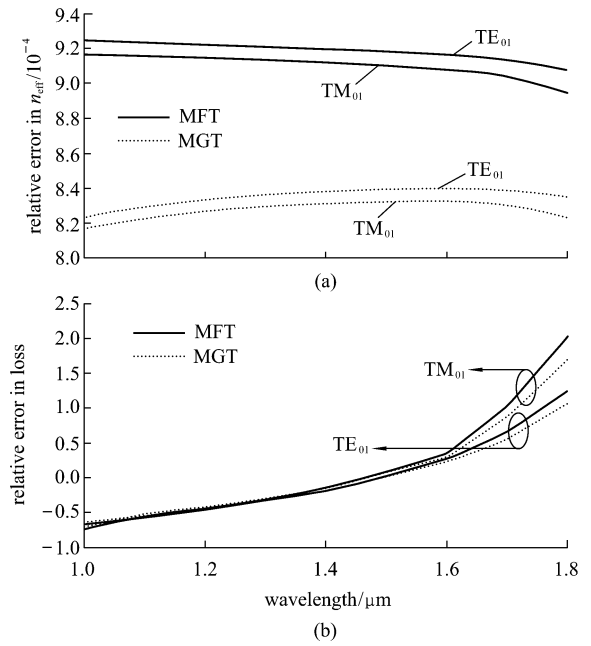


Fig. 6 (a) Relative error in n_{eff} value for MFT and MGT approximation models; (b) relative error in loss

new dimension for controlling waveguiding properties. In particular, with a specific Bragg fiber example, we show how the TE₀₁ and TM₀₁ modes can be discriminated by using a cylindrically layered metamaterial. Such a specialty fiber can be deployed for selecting one particular mode of interest from otherwise a group of nearly degenerate modes as in a conventional step-index fiber. Furthermore, we have assessed the accuracy properties of two metamaterial homogenization methods, namely the mean field theory and the Maxwell-Garnett theory, for this particular class of propagation problems. It is found that MGT is, in general, more accurate than MFT. However, the advantage of MGT over MFT is not significant. Modal properties derived using both homogenization methods show acceptable accuracies with results calculated using full fiber structure for many practical purposes. Of course, the validity of this statement depends on the particular problem at hand. The accuracy property of the two homogenization methods for fibers with higher index contrast is a subject of future study.

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References

1. Shelby R A, Smith D R, Schultz S. Experimental verification of a negative index of refraction. *Science*, 2001, 292(5514): 77–79

2. Shalaev V M. Optical negative-index metamaterials. *Nature Photonics*, 2006, 1: 41–48
3. Birks T A, Knight J C, Russell P S. Endlessly single-mode photonic crystal fiber. *Optics Letters*, 1997, 22(13): 961–963
4. Yan M, Shum P. Antiguiding in microstructured optical fibers. *Optics Express*, 2004, 12(1): 104–116
5. Koshiba M, Saitoh K. Simple evaluation of confinement losses in holey fibers. *Optics Communications*, 2005, 253(1–3): 95–98
6. Wang A, George A, Liu J, Knight J. Highly birefringent lamellar core fiber. *Optics Express*, 2005, 13(16): 5988–5993
7. Hu J, Yan M, Shum P. Birefringent optical fiber with a photonic-crystal core. In: *Proceedings of Australian Conference on Optical Fibre Technology (ACOFT)*, 2006, 60–62
8. Yu X, Shum P, Yan M, Ren G. Silica based birefringent large mode area fiber with a nanostructure core. *IEEE Photonics Technology Letters*, 2008, 20(4): 246–248
9. Yu X, Shum P, Ngo N, Tong W, Luo J, Ren G, Gong Y, Zhou J. Silica-based nanostructure core fiber. *IEEE Photonics Technology Letters*, 2008, 20(2): 162–164
10. Yan M, Shum P. Analysis of perturbed Bragg fibers with an extended transfer matrix method. *Optics Express*, 2006, 14(7): 2596–2610
11. Yeh P, Yariv A, Marom E. Theory of Bragg fiber. *Journal of the Optical Society of America*, 1978, 68(9): 1196–1201
12. Johnson S, Ibanescu M, Skorobogatiy M, Weisberg O, Engeness T, Soljacic M, Jacobs S, Joannopoulos J, Fink Y. Low-loss asymptotically single-mode propagation in large-core OmniGuide fibers. *Optics Express*, 2001, 9(13): 748–779