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Modeling a Fully Polarized Optical Fiber Suitable for Photonic Integrated Circuits or Sensors

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Abstract: A method is developed to make an optical fiber that only transmits fully linearly polarized light and maintains the polarization state. The method for efficient ingesting laser into this fiber is also reported. Using an optical fiber with a prism head, we can compress a plane wave into the thin rectangular cross-section fiber, and the light intensity within the fiber is much larger than that of the incidence wave. Our finite-difference time-domain (FDTD) simulation results show that the compressed light in the fiber becomes fully polarized and maintains the polarization state, and can be well coupled out by the resonance rings. This method is suitable for developing highly efficient polarization-maintaining optical fibers in a much simpler way, for applications in photonic integrated circuits or optical sensors.

Keywords: fiber optics and optical communications; polarization-maintaining fibers; photonic integrated circuits; optical sensors

1. Introduction

Polarization-maintaining fibers (PMFs) that allow the input light to propagate only in one polarization mode have many applications in optical communication systems [1,2], optical fiber interferometry [3], and optical devices requiring high polarization stability, such as modulators. Optimizing the polarization stability of PMFs [4,5] is one of the critical considerations in developing PMF-dependent systems. Traditionally, the PMFs' characteristic of maintaining the polarization throughout the propagation process is achieved by inducing stresses in the material itself during the manufacturing phase [1]. That is, apart from the fiber core, this fiber also contains stress rods that can cause a strong built-in birefringence so that only one polarization state of light can transmit through the fiber. Thus, when PMFs are terminated using fiber connectors, stress rods must align with the connector key correctly. Also, when it comes to splicing, the alignment of the stress rods needs great care. These make the development of the optical system difficult. The second critical consideration in developing PMF-dependent systems is to improve the efficiency of coupling PMFs to laser beams [6,7], including using beam-shaping optics. Our report will focus on these two issues in this study.

In Section 2, the method to efficiently ingest and polarize a plane light wave into an optical fiber is introduced. The finite-difference time-domain (FDTD) method [8–10] with a uniaxial perfectly matched layer (UPML) absorbing boundary condition (ABC) [11] is used to simulate the method's effect on collecting and transmitting polarized light through a fiber. Numerical results are given in Section 3. And in Section 4, we give a summary and conclusions.

2. Method

To efficiently couple and polarize a plane light wave into an optical fiber, we assumed an optical fiber with a prism receiving head, as shown in Figure 1. The optical fiber had a rectangular cross-section; its width was λ and thickness was $\lambda/2$, where λ denotes the light's wavelength inside the optical material of the fiber. The prism receiving head had

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the same optical properties and width as the fiber. The length (l) and the half aperture angle (θ) of the receiving prism of the fiber determines the coupling efficiency, i.e., the wave amount received by the system. However, the light intensity in the fiber is also affected by the refractive index of the fiber, the aperture angle, and the polarization status of the incidence, due to the backscatter from the oblique surface of the prism, and the polarization characteristic of the fiber. In this study, we assumed a fiber of silicon with incidence light at the near infrared (IR) wavelength of λ_0 = 1.5 μm. Utilizing the refractive index of 3.5 of silicon at this wavelength, the wavelength inside the silicon was $\lambda = \lambda_0/3.5$, and the half aperture angle of the fiber's receiving head (θ) was set to 3.5°. The length (l) of the receiving head was set to only 5.5 λ. We used the finite-difference time-domain (FDTD) method [8–10] to simulate light's interaction with this system. The FDTD spatial cubic cell size was set to $\delta = \lambda/10$ and the time step was set to $\delta t = \delta/(2c)$, where c denotes light speed in free space.

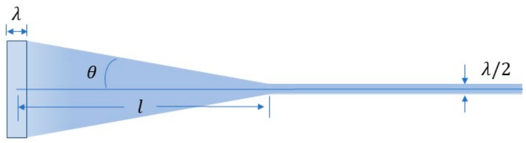

Figure 1. Illustration of the optical fiber and its width, thickness, and the half aperture angle of its receiving end.

The fiber and the receiving head prism are positioned in the FDTD computational domain as illustrated in Figure 2. We set periodic boundary conditions (PBC) [12] at 4 sides of the computational domain around the fiber to simulate a large array of this system. Along the light's incidence direction, the computational domain was truncated by two 6-spatial-cell-thick uniaxial perfectly matched layer (UPML)-absorbing boundaries [11]. The fiber is effectively an infinitely long one since its other end is inside the UPML, which has negligible reflection. A profile of the material property of the computational domain is shown in Figure 3. The perfect conductor is arranged around the receiving head prism to block light leakage before entering the rectangular fiber. The lower fiber has identical geometric parameters and optical properties to those of the upper one. The two resonance rings have the same refractive index as that of the fibers. The upper ring's central radius (i.e., the radius at the ½ thickness of the ring) is *17* λ, and the lower ring's central radius is *13* λ. The radii of the two rings were arbitrarily chosen as exemplary cases. The radii of the rings affect the coupling length of the fibers, thus exchanging the position of the two rings could change the resonance effect. The distance between the outer edge of the ring and the edge of the straight fiber is one FDTD cubic cell δ. All the optical fibers are on the same z plane.

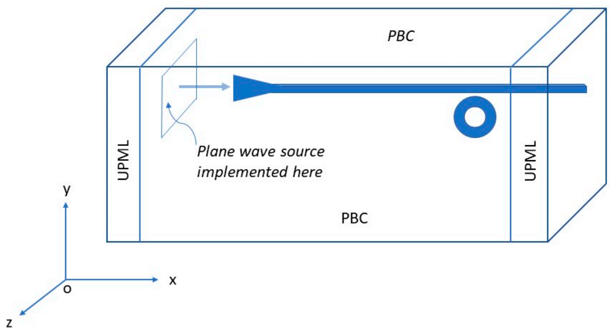

Figure 2. Illustration of the optical fiber, light source implementing plane, uniaxial perfectly matched layer (UPML)-absorbing boundary conditions (ABC) and periodic boundary conditions (PBC) in the computational domain of the FDTD method.

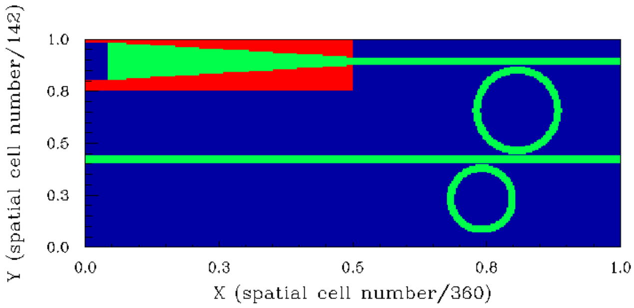

Figure 3. The material refractive index profile in the computational domain. The green color denotes fiber material, the red color denotes perfect conductor, and the blue color denotes free space.

3. Numerical Results

We implemented a plane wave with electric field amplitude of *1* at the wave source plane as illustrated in Figure 2. At first, we simulated a y-polarized light's incidence on the system. Figure 4 shows that, after 300 FDTD time steps, the wave cannot effectively enter the fiber and the light's field inside the fiber is nearly zero. This is because in the y direction the fiber has only a half-wavelength thickness, reaching the limit of diffraction, and the electric field oscillating in the y direction and reflected by the fiber edge has a mostly destructive phase difference inside the fiber, thus light cannot propagate.

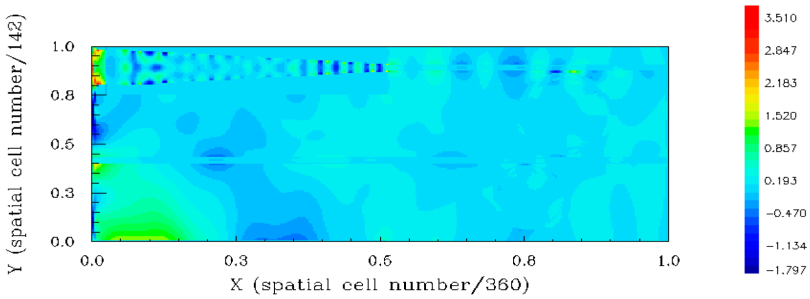

Figure 4. The finite-difference time-domain (FDTD) result for incidence plane light fully polarized in the y direction (E_y only). After 300 time steps of simulation, the light intensity inside the fiber is still nearly zero, which means the y-direction polarized light cannot enter the fiber effectively.

We then simulated a z-polarized light's incidence on the system. Figure 5 shows the numerical results after 600 FDTD time steps. We can see that the wave is well ingested into the rectangular fiber. The amplitude of the electric field can be as large as *~2.0*. This means the light's intensity inside the rectangular fiber is about four times that of the incidence. The micron-sized receiving head prism works very efficiently to receive light. Additionally, the light entering the fiber keeps good mode and can be well coupled out by resonance rings. It means that this design can be applied in a photonic integrated circuit device. Also, comparing the results in Figures 4 and 5, we can conclude that this system can well polarize the incident light, i.e., only z-polarized light can transfer efficiently in the system. This can be applied to make polarization-maintaining fibers in a much simpler way than that of using stress rods [1]. Note that our simulations of the resonance rings' central radii are simply set as integer numbers of wavelengths inside the macro silicon material (i.e., $\lambda = \lambda_0/3.5$), not the effective wavelength based on effective indices (e.g., [13]) of the specific resonance rings. As such, the light is not completely coupled out and there is still some residue propagation inside the straight fibers after the coupling processes. Note here that in these modeling studies, we assume a plane incidence wave for simplicity; since the fiber is very thin, this should not cause significant difference from the use of a Gaussian beam.

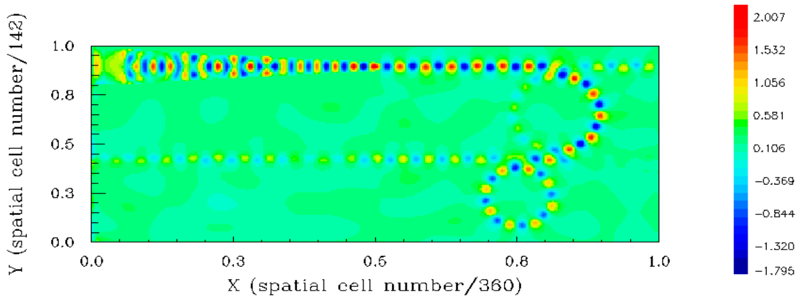

Figure 5. The finite-difference time-domain (FDTD) result for incidence plane light fully polarized in z direction (E_z only). After 600 time steps of simulation, the compressed light in the fiber keeps good transfer mode and can be well coupled out by resonance rings. The light intensity inside the fiber is ~4 times of that of incidence.

4. Conclusions

In this study, a method is developed to compress and polarize a plane light wave into an optical fiber. Using an optical fiber with a prism receiving head, we can compress plane wave into a thin rectangular cross-section fiber, and the light intensity inside the fiber is much larger than the incidence wave. We assume a fiber of silicon with incidence light at the near infrared (IR) wavelength of $1.5\ \mu m$. Utilizing a refractive index of 3.5 of the silicon material at this wavelength, the half aperture angle of the fiber's receiving head (θ) is set to 3.5°. The fiber thickness and width are set as a half wavelength and one wavelength, respectively (the wavelength here is the light wavelength in the fiber material). Our FDTD simulation results show that the compressed light in the fiber becomes well polarized and keeps a good transfer mode that can be well coupled out by resonance rings. The light intensity inside the fiber can be changed by adjusting the length of the prism while preserving the aperture angle. This method is suitable for developing highly efficient polarization-maintaining optical fibers in a much simpler way, for applications in photonic integrated circuits or optical sensors. Note here that this is only a modeling study. But, experiments can be done by depositing a silicon film on a copper substrate [14] and photoetching it following the shape and size of this design.

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Data Availability Statement: Data underlying the results presented in this paper are available on the computer of Donghai Laboratory.

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Conflicts of Interest: The author declares no conflict of interest.

References

1. Noda, J.; Okamoto, K.; Sasaki, Y. Polarization-maintaining fibers and their applications. *J. Light. Technol.* **1986**, *4*, 1071–1089. [CrossRef]
2. Xu, F.; Ma, X.; Zhang, Q.; Lo, H.-K.; Pan, J.-W. Secure quantum key distribution with realistic devices. *Rev. Mod. Phys.* **2020**, *92*, 025002. [CrossRef]
3. Pan, J.W.; Chen, Z.B.; Lu, C.Y.; Weinfurter, H.; Zeilinger, A.; Żukowski, M. Multiphoton entanglement and interferometry. *Rev. Mod. Phys.* **2012**, *84*, 777–838. [CrossRef]
4. Walker, G.; Walker, N. Alignment of polarisationmaintaining fibres by temperature modulation. *Electron. Lett.* **1987**, *23*, 689–691. [CrossRef]
5. Arora, P.; Agarwal, A.; Gupta, A.S. Simple alignment technique for polarisation maintaining fibres. *Rev. Sci. Instrum.* **2011**, *82*, 125103. [CrossRef] [PubMed]
6. Nyman, R.A.; Varoquaux, G.; Villier, B.; Sacchet, D.; Moron, F.; Le Coq, Y.; Aspect, A.; Bouyer, P. Tapered-amplified antireflectioncoated laser diodes for potassium and rubidium atomic-physics experiments. *Rev. Sci. Instrum.* **2006**, *77*, 033105. [CrossRef]
7. Bolpasi, V.; Von Klitzing, W. Double-pass tapered amplifier diode laser with an output power of 1 W for an injection power of only 200 µW. *Rev. Sci. Instrum.* **2010**, *81*, 113108. [CrossRef] [PubMed]

8. Yee, K.S. Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media. *IEEE Trans. Antennas Propag.* **1966**, *14*, 302–307.
9. Sun, W.; Fu, Q.; Chen, Z. Finite-difference time-domain solution of light scattering by dielectric particles with a perfectly matched layer absorbing boundary condition. *Appl. Opt.* **1999**, *38*, 3141–3151. [CrossRef] [PubMed]
10. Sun, W.; Loeb, N.G.; Fu, Q. Finite-difference time-domain solution of light scattering and absorption by particles in an absorbing medium. *Appl. Opt.* **2002**, *41*, 5728–5743. [CrossRef] [PubMed]
11. Sacks, Z.; Kingsland, D.; Lee, R.; Lee, J.-F. A perfectly matched anisotropic absorber for use as an absorbing boundary condition. *IEEE Trans. Antennas Propag.* **1995**, *43*, 1460–1463. [CrossRef]
12. Sun, W.; Videen, G.; Lin, B.; Hu, Y. Modeling light scattered from and transmitted through dielectric periodic structures on a substrate. *Appl. Opt.* **2007**, *46*, 1150–1156. [CrossRef] [PubMed]
13. Savolainen, J.-M.; Grüner-Nielsen, L.; Kristensen, P.; Balling, P. Measurement of effective refractive-index differences in a few-mode fiber by axial fiber stretching. *Opt. Express* **2012**, *20*, 18646–18651. [CrossRef] [PubMed]
14. Jasinski, J.M.; Gates, S.M. Silicon chemical vapor deposition one step at a time: Fundamental studies of silicon hydride chemistry. *Acc. Chem. Res.* **1991**, *24*, 9–15. [CrossRef]