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Study the properties of metal-cladding nano-size optical fiber based on a new implementation of finite-difference time-domain

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ABSTRACT

The properties of metal-cladding nano-size optical fiber are investigated using a new implementation of finite-difference time-domain, in which the amendment form of Drude is used. The results reveal that the thickness of Ag-film greater than 110 nm is enough to shield the interference between nano-size fibers when the wavelength of incident light is 632 nm. This proves that the metal-cladding nano fiber has stronger tight-confinement ability than the air-cladding nano fiber. Meanwhile, although the confinement ability of metal-cladding non-uniform fiber declines slightly with the angle α between fiber surface and horizontal plane, the metal-cladding fiber can solve the problem of light energy loss caused by diameter non-uniformity in transmission process greatly. The experimental results reveal that metal-cladding nano-size optical fiber can improve transmission efficiency greatly. The behavior of metal-cladding nano fiber demonstrated may provide actual reference value for the development of optical applications of nano fiber.

1. Introduction

In the past few decades, dielectric optical waveguides with widths or diameters from micrometers to millimeters used as transmission medium or components of optoelectronic devices have been widely used in the field of optical communication, optical sensing and optical power delivery systems [1–3]. There is a growing research interest in optical circuits at the nanometer scale for future integration of optical optoelectronic and electronic devices. For this goal, however, the typical dimensions of conventional dielectric waveguides are dictated by diffraction, therefore limiting dense integration. Subwavelength-diameter silica wires are potential candidates for nanoscale optical elements with sizes much smaller than the diffraction limit.

Nano-size optical fiber as one of the most important integrated photonic devices is used as sensors [4,5], nanowire lasers [6], low-loss light transmission medium [7] and so on. Recent studies have shown that [8], the diameter of air-cladding nano-size optical fiber should be smaller than light wavelength for single-mode operation. For smaller diameters, more light propagates outside the core as an evanescent wave. Evanescent wave propagation is extremely useful for enhancing the performance of devices such as optical coupling. Modeling of evanescent coupling have wide applications, such as power division, all fiber interferometric sensors [9,10]. However, because of strict requirements on surface roughness and diameter uniformity, the fabrication of the low-loss fibers with subwavelength diameters still remains challenging [11–14]. Until 2003, the silica wires with diameters of 50–550 nm reported have much better uniformity of diameter and surface smoothness [15].

However, in most cases, a real wire could not be ideally uniform, especially when the width or diameter of the waveguide is very small [8]. In order to overcome the problem of light energy loss of transmission process, we coat a high reflectivity metal film on surface of the wires. However, in addition to be studied as probes for scanning near-field optical microscopy (SNOM) [16] and optical sensors [17], metal-cladding nanofiber seldom be investigated in recent years.

The finite difference time domain (FDTD) technique has been widely used to analyze electromagnetic phenomena. Yee introduced an FDTD scheme applied to Maxwell's equations in 1966 [18]. Recently, with the progress of computational work, the numerical analysis has come to be recognized as a powerful tool for computing the optical properties of arbitrary, irregular structures with subwavelength features. Luebbers has presented an efficient method to include frequency-dependent materials in FDTD calculations based on recursive evaluation of the convolution of the electric field and susceptibility [19].

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In this paper, using FDTD method presented by Luebbers, we investigated the guiding properties of metal-cladding nanofiber in detail. In order to improve the accuracy of simulation, we use the amendment form of Drude model which has never been reported in FDTD method as far as we know. It is found that the results reproduce the expected values, indicating that light energy is tightly confined inside metal-cladding nanofiber. The experimental results illustrate that metal-cladding nanofiber can reduce loss caused by diameter non-uniformity. The results are actual reference value for the development of new type of fiber equipments.

2. Approach

2.1. Discussion about metal frequency-dependence model

The traditional FDTD method will be no longer applied due to optical properties of metal. Choosing a suitable metal dispersion model which can improve the accuracy of computational results is one of key steps of simulation. Now some typical metal dispersion models are commonly used, such as Debye model [20], Lorentaz model, Drude model [21], Lorentaz–Drude model and the amendment form of each model. Lorentaz model and Drude model are widely used.

Lorentaz model based on classical physics was presented by physicist Lorentaz in 19th century. For metal, it is assumed that the elastic force between electric charges is generated by electric field; free electrons are attracted or bounded through the elastic force. The model is fully capable of describing the nature of metal; however, experiments prove that, if we use the model to achieve the desired accuracy, more intrinsic frequency should be considered [22]. Computational efficiency will decline with the number of intrinsic frequency increasing. In order to achieve higher accuracy, we must cost a lot of computers resources and time. Therefore, choosing the model is not wise for FDTD calculation.

Drude model is a simplified form of Lorentaz model. It is assumed that the action of electrons complies with Newton's laws under electromagnetic fields, and scatter to other directions in the elastic collision process. However, the accuracy of the model is not high [23]. In order to improve the accuracy of simulation, we use the amendment form of Drude model. Dispersion equation is given

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{j\omega\nu_c + \omega^2} = \varepsilon(\infty) - \chi(\omega) \tag{1}$$

where ω_p is the plasma frequency, ν_c is the collision frequency, $\varepsilon(\infty)$ is infinite-frequency dielectric constant and equal to 1, $\chi(\omega)$ is susceptibility. Experiments proved that the amendment form of Drude model can get very high accuracy in the target band [24,25], and it is simplified easily in FDTD calculation.

Take silver for example, its parameters are set as $\omega_p = 9.5\,\text{eV}$, $\nu_c = 0.0987\,\text{eV}$ [27]. According to Fig. 1, the simulation results are agreed with the measured values of the complex dielectric constants, when $\varepsilon(\infty)$ is 5.5. Fig. 1 also shows that when wavelength is greater than 1200 nm, the dielectric constants obtained from amendment form of Drude model are not too consistent with the measured values; while in the visible band, the values of the model fit well with the measured values.

2.2. Discussion about the derivation of FDTD method for metal

In dispersive materials in which the real part of the electric permittivity (ε) is negative, and for monochromatic light dispersive effects must be taken into account, recursive convolution (RC) FDTD is used. The relationship of electric displacement and electric field can be described as [28]

$$D(\omega) = \varepsilon_0 \varepsilon(\omega) E(\omega) \tag{2}$$

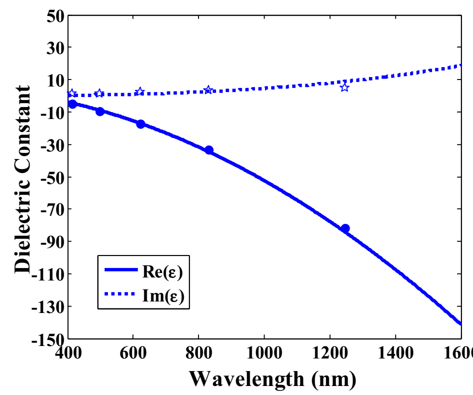

Fig. 1. The complex dielectric constants of Ag. Solid and dash lines represent the real part and imaginary part of the results obtained from the amendment form of Drude model, respectively; filled black circles and five-pointed star represent the real part and imaginary part of measured dielectric constants, respectively [26].

where the dielectric constants are obtained from the amendment form of Drude model. The time-domain behavior of electric displacement is obtained by taking the inverse Fourier transform on both sides of Eq. (2), $D(t)$ is given by

$$D(t) = \varepsilon_0 \varepsilon(t) \times E(t) \tag{3}$$

$\chi(\omega)$ of Eq. (1) is obtained using the inverse Fourier transform of the typical signals [29].

$$\begin{aligned} \chi(t) &= F^{-1}[\chi(\omega)] \\ &= F^{-1}\left[\frac{\omega_p^2}{\omega(\omega + j\nu_c)}\right] = \omega_p^2 F^{-1}\left[\frac{1}{\nu_c \omega j} + \frac{1}{\nu_c(\nu_c - \omega j)}\right] \\ &= \frac{\omega_p^2}{\nu_c}\left(1 - e^{\nu_c t}\right) U(t) \end{aligned} \tag{4}$$

where $U(t)$ is a unit step function.

Eq. (3) is discretized in keeping with the FDTD time-stepping scheme. We assume that Δt is the minimum time step, n represents the total time steps corresponding to t, $t = n\Delta t$. Over any single interval Δt, the electric field E can be considered to be constant. Using Eqs. (1), (3) and (4), the electric displacement current can be expressed as

$$\begin{aligned} D(t) &= \varepsilon_0 \varepsilon_\infty \delta(t) \times E(t) - \varepsilon_0 \chi(t) \times E(t) \\ &= \varepsilon_0 \varepsilon_\infty E^n - \varepsilon_0 \int_0^t \chi(\tau) E(t - \tau)\, d\tau \\ &= \varepsilon_0 \varepsilon_\infty E^n - \varepsilon_0 \psi^n \end{aligned} \tag{5}$$

where

$$\psi^n = \sum_{m=0}^{n-1} E^{n-m} \frac{\omega_p^2}{\nu_c^2} [\Delta t \nu_c - (e^{\nu_c(m+1)\Delta t} - e^{\nu_c m \Delta t})] \tag{6}$$

For passive components, the Maxwell equations are expressed as

$$\nabla \times \vec{E} = -\mu \frac{\partial \vec{H}}{\partial t} \tag{7}$$

$$\nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} \tag{8}$$

It is assumed that all the physical parameters are independent on z axis in two dimensional coordinate, then $\partial/\partial z = 0$. In the TM mode, $E_x = E_y = H_z = 0$, Δx and Δy represent the space step in the