Modeling of micro-diameter-scale liquid core optical fiber filled with various liquids

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Abstract: This paper gives the simulation results on micro-diameter-scale liquid core optical fiber (LCOF) filled with different kinds of liquids. The nonlinear and group velocity dispersion (GVD) properties of the micro-diameter-scale LCOF are achieved. The simulation of supercontinuum generation of LCOF is also obtained. The calculations show that LOCF can provide huge nonlinear parameter and large span of slow varying GVD characteristics in the infrared region, which have potential applications in optical communications and nonlinear optics. Besides, LOCF has advantage of easy fabricating and robustness compared with silica nano-wire.

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References and Links

1. Introduction

The single-mode guiding properties of micro- or submicro-diameter silica fibers show the tight-confinement ability and a slow variation with small group velocity dispersion (GVD) values in the anomalous dispersion [1]. It has a large number of applications in optical sensing, pulse compression, optical frequency metrology and so on [2-7]. For applications in nonlinear optics, larger nonlinear parameter ($\gamma$) is preferred. There are two methods to achieve large nonlinear parameter ($\gamma$) in a fiber. One is to decrease the effective area of fiber, and the other method is to choose the material with large nonlinear coefficient ($n_2$). In the first approach, photonic crystal fiber and tapered silica fiber are fabricated to decrease the effective area, so that the nonlinear parameter ($\gamma$) can be greatly enhanced [1, 8]. Unfortunately, the high cost of PCF and the fragileness of tapered fiber prevent them from large-scale manufacturing and further commercial use. On the other hand, because the liquids have much higher nonlinear optical coefficient, people filled the hollow fiber with high index liquids to form a liquid core optical fiber (LCOF) [9]. Stimulated Raman Scattering and supercontinuum are observed in LCOF owing to the large nonlinearity of the liquid [10-15]. The diameter of the LCOF reported today is usually 10-100 $\mu$m. It can be expected that when diameter of the LCOF reaches to micrometer or sub-micrometer scale, huge nonlinear parameter ($\gamma$) can be obtained owing to both small effective area and high nonlinear optical coefficient. As the development of fabrication of taper silica fibers [16], the diameter of the hollow hole can also easily reach to micro-diameter-scale while the outer silica diameter remains as large as about ten micrometers. In additional, the GVD of the tapered fiber can be shifted by variation of the
diameter of fiber, and can also be adjusted by coated with thin dielectric or immersed into different liquids [17-20,21].

In our previous work [21], we have investigated the propagation properties of micro-diameter-scale LCOF and compare them with micro-diameter-scale tapered fiber. However, in this paper, we pay more attentions on LCOF’s high nonlinear parameter and its potential use in nonlinear optics, especially in supercontinuum generation. We theoretically demonstrate the propagation properties of a new micro-diameter-scale fiber by filling different high index liquids. By the numerical simulations of a 3-layer-structured cylindrical waveguide, we compared the nonlinear parameter (γ) and GVD of the fundamental mode in the micro-diameter-scale LCOF filled with four kinds of different high index liquids (carbon disulfide, toluene, benzene, nitrobenzene). A simple way to enhance the nonlinear parameter (γ) or shift the GVD of the fiber is provided by adjusting the diameter or making use of different liquids. As a result, the supercontinuum generation can be controllable.

2. Mathematic model for micro-diameter-scale LCOF.

The mathematic model in our simulation is illustrated in Fig. 1. The micro-diameter-scale liquid core optical fiber is a cylindrical structure of translation symmetry involving three regions. (Fig. 1(a)): a liquid core (e.g. carbon disulfide) with radius a2, a silica cladding with radius from a2 to a1 and the infinite air cladding, where the D represents the diameter of the liquid core. As an example, we assume the ratio of a2 and a1 is 12.5/0.8 in our calculations. The refractive indices of the liquid core, the silica cladding and the air cladding are n2, n1 and n0, respectively. (Fig. 1(b)).

Solving Maxwell’s equation in cylindrical coordinates (r, Θ, z) leads to the expressions for the components of the electromagnetic field for the mth mode. According to the boundary condition, The longitudinal component of the electromagnetic field and the azimuthal component of the electromagnetic field must be continuous at the inner and outer cylinder surfaces (r=a1 and r=a2). Then we can get eight linear equations satisfied. This equation leads a (8×8) matrix which determinant must be equal to zero to ensure a nontrivial solution. At last, the dispersion equation can be obtained [22]. In this paper, only the features of fundamental mode are discussed.

From the reference [18, 23], Sellmeier equations (1) were fitted for the refractive index for the four kinds of liquids:

\[
\frac{\lambda^2}{n^2} - \frac{\lambda^2}{n_0^2} = C_1 \left( \frac{\lambda^2}{n_1^2} - \frac{\lambda^2}{n_0^2} \right)^{\frac{1}{3}}
\]

\[
\frac{\lambda^2}{n^2} - \frac{\lambda^2}{n_0^2} = C_2 \left( \frac{\lambda^2}{n_2^2} - \frac{\lambda^2}{n_0^2} \right)^{\frac{1}{3}}
\]

Fig. 1. Mathematic model of the micro-diameter-scale liquid core optical fiber. (a) Cross-section view and (b) refractive index profile of the fiber.
GVD of the fibers is given by the following equation (2) [24]:

\[
\text{Dispersion} = \frac{-2\pi c}{\lambda} \frac{d^2\beta}{d\omega^2},
\]

(2)

3. The nonlinear parameter (\(\gamma\)) of the fundamental mode.

The nonlinear parameter \(\gamma\) is important for investigating the nonlinear properties of the fiber. Especially in some nonlinear process, such as self-phase-modulation, Stimulated Raman Scattering and four wave mixing. It can be evaluated as following equation [24]:
In this formula, the effective area of the mode $A_{\text{eff}}$ can be obtained.

$$ \gamma = \frac{n_2 \omega}{c A_{\text{eff}}} $$

$$ A_{\text{eff}} = \frac{\iint_{-\infty}^{\infty} |F(x, y)|^2 \, dx \, dy}{\iint_{-\infty}^{\infty} |F(x, y)|^4 \, dx \, dy}, $$

Here, $n_2$ is the nonlinear refractive index of the fiber material, the $F(x, y)$ is the modal field distribution function, $c$ is the speed of the light in vacuum, and $\omega$ is the given frequency. Among the four liquids we used, the $n_2$ of two liquids are available and presented as [25] (they are obtained in the short pulse duration which is less than 200fs):

- carbon disulfide: $\hat{n}_2 = 1.2 \times 10^{-18} \text{m}^2/\text{w}$
- toluene: $\hat{n}_2 = 1.3 \times 10^{-19} \text{m}^2/\text{w}$

Fig. 3. The effective area of the mode of the micro-diameter-scale liquid core optical fibers filled with carbon disulfide or toluene (a) at the wavelength of 800nm; (b) at the wavelength of 1550nm.
Figure 3 and 4 describes the value of the effective area of the mode and the nonlinear parameter $\gamma$ in the micro-diameter-scale LCOF filled with carbon disulfide or toluene at the wavelength of 800nm and 1550nm, respectively. All the micro-diameter-scale LCOF filled the two kinds of different liquid have a very large nonlinear parameter $\gamma$ when the inner diameter is around one micrometer. It is shown that there is a maximum value at a certain diameter. For example, when the diameter is 0.5\,$\mu$m with the wavelength=800nm, the nonlinear parameter of the micro-diameter-scale LCOF filled with the carbon disulfide shows the maximum value which is about 18000\,W\,km\,^{-1}. And with the wavelength=1550nm, 3250\,W\,km\,^{-1}, respectively. The fiber presents a stronger nonlinearity with the wavelength=800nm. By filling different liquids or adjusting the diameter of the fiber, the value of the nonlinear parameter ($\gamma$) can vary from about 50\,W\,km\,^{-1} to about 18000\,W\,km\,^{-1} and with the wavelength=1550nm, the value of $\gamma$ varying from about 10\,W\,km\,^{-1} to about 3250\,W\,km\,^{-1}. In the previous studies, the nonlinear coefficient $\gamma$ of the some kinds of high nonlinear fibers has been investigated. For example, the nonlinear coefficient $\gamma$ is about 35\,W\,km\,^{-1} in silica high nonlinear holey fiber, measured at 1550nm with a pulsed, dual-frequency...
beat-signal nonlinear spectral enrichment technique [26]; typical values of $\gamma$ of the Bi$_2$O$_3$ fiber is 64 W$^{-1}$ km$^{-1}$ and for As$_2$S$_3$ the $\gamma$ is measured as 162 W$^{-1}$ km$^{-1}$ [27]. The nonlinear parameter in the micro-diameter-scale LCOF is expected to have a much larger value than traditional silica fibers or other conventional highly nonlinear fibers.

4. Supercontinuum simulation

Considering the broad transparency and high nonlinear in infrared region, we simulate the SC generation in micro-diameter-scale liquid core optical fiber filled with carbon disulfide. The Nonlinear Schrödinger equation is expressed as follows:

$$\frac{\partial A}{\partial z} = \left( -\frac{i}{2} \beta_2 \frac{\partial^2 A}{\partial T^2} + \frac{1}{6} \beta_3 \frac{\partial^3 A}{\partial T^3} - \frac{\alpha}{2} \right) + i\gamma \left[ |A|^2 + \frac{1}{\omega_0} \frac{\partial}{\partial T} \left( |A|^2 A \right) - T_R \frac{\partial |A|^2}{\partial T} \right] A \ (6)$$

On the right side of equation (6), the first term represents dispersion and absorption of the fiber and the second term shows the nonlinear effect, including self-steering and Raman Effect. To simplify the calculation, we neglect absorption ($\alpha$), the third-order of $\beta$ ($\beta_3$) and Raman Effect ($T_R$) in the equation. The absorption bands in UV range for the two liquid are listed in the references [32-33]. By means of split-step Fourier Method, we successfully solve equation (6) and give out the simulation result as following Fig. 5.

![Fig. 5. The calculated output spectrum generated by a 1mm long LCOF with 0.6μm inner diameter full of (a) carbon disulfide and (b) toluene with a pump wavelength of 800nm, and a pulse duration of 100fs, with different input peak power P](image)

The SC spectrum generated by a 1mm long micro-diameter-scale LCOF with 0.6μm inner diameter full of carbon disulfide and toluene with a pump wavelength of 800nm, and a pulse duration of 100fs with different input peak power is shown in Fig. 5 (a) and (b). Here, we neglected the effect of TPA and thermal lensing to the nonlinear response mainly because of the short operation length and the relatively low peak power. Comparing with the previous results in which 5cm long fiber is employed [18], the micro-diameter-scale LCOF needs much shorter length on the same condition.

5. Conclusion

In this paper, we discussed the nonlinearity and GVD characterization of micro-diameter-scale liquid core optical fiber filled with different kinds of liquids. These new kinds of micro-diameter-scale LCOF are easier to fabricate than traditional taper fibers owing to the much larger outer diameter. The fibers show huge nonlinear parameters ($\gamma$) and tunable GVD. Because the technique to fill the tiny hole of a hollow fiber with liquids has been taken into
practice [28-31], we believe that micro-diameter-scale LCOF will have a potential application in the communication and nonlinear optics.

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