Tunable and low bending loss of liquid-core fiber

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The liquid-core fiber with relatively high refractive index difference between the core and cladding is proven to be bending insensitive. The single mode condition and bending loss of the fiber with a mixture of toluene and chloroform as its core material are studied. The results show that the bending loss of this fiber is not only much smaller than the conventional silica single mode fiber but also can be tuned by the temperature and liquid mixture ratio. This kind of fiber may find its potential applications in all-optical network.

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Optical fibers have extensive commercial applications in communications and play an irreplaceable role in the telecom network[1−10]. However, the loss induced by fiber bending will clog the telecom network's shift from copper wires to all-optical network which is naturally required in the following years for the increasing number of subscribers and potential growth of bandwidth[11,12]. Therefore fibers with low bending loss are urgently demanded. The key point to realize low bending loss is to strongly confine the mode field within the bent fiber. A number of different methods have been proposed and studied both theoretically and experimentally to fulfill this purpose, such as tapered fiber, etched fiber, hole assisted fiber, and so on[13−19]. Recently, the design and tolerance analysis have also been studied for a hole assisted and trenched bend insensitive fiber[17−19] which can act as good guidance for practice. The simulation results show a strong advantage of these fibers over conventional single mode fibers when bent. However, these fibers are still complicated to produce for practical applications.

In this letter, based on the idea that a strong confined mode field can be obtained by high refractive index difference between the core and cladding of the fiber, we propose a liquid-core fiber as our model. Liquid-core fiber was first studied in 1970[20] and has received hot attractions from various regions since then[21,22]. The fiber was mainly made by filling liquid into a hollow capillary and the liquid-core waveguides were successfully fabricated by soft lithography in the early time[23]. But since the hollow fibers with different core radius from 1 to 25 μm are already commercially available now (Polymicro Technologies), the fabrication of liquid-core fiber becomes easier. Liquid filling can be achieved spontaneously by capillary actions or by a high pressure system to make the process faster. In order to match with the conventional single mode fiber which is already widely used in the optical fiber network, we will emphasize on the property of our liquid-core fiber with a core radius of 4 μm. Because the refractive index of liquids is temperature dependant, the bending loss of our fiber will bear the advantage of temperature-tunable. In the following simulation, we use a mixture of two different liquids (toluene and chloroform) as the core material of the fiber, so the bending loss is also tunable by tuning the concentration of toluene in the mixture.

The theoretical model of our simulation is illustrated in Fig. 1, where n_1 and n_2 are the refractive index of fiber core and cladding, respectively, a is the radius of fiber core, and we assume the radius of cladding to be infinite. The bending loss of such a fiber is explained by the property of refractive index distribution which results from two different origins. The first is the refractive index of the straight fiber shown in Fig. 1(b), and the second is that induced by fiber bending which is larger outside than inside the bent region. That is, for a bent fiber the refractive index of cladding may be equal to or even larger than the effective propagating refractive

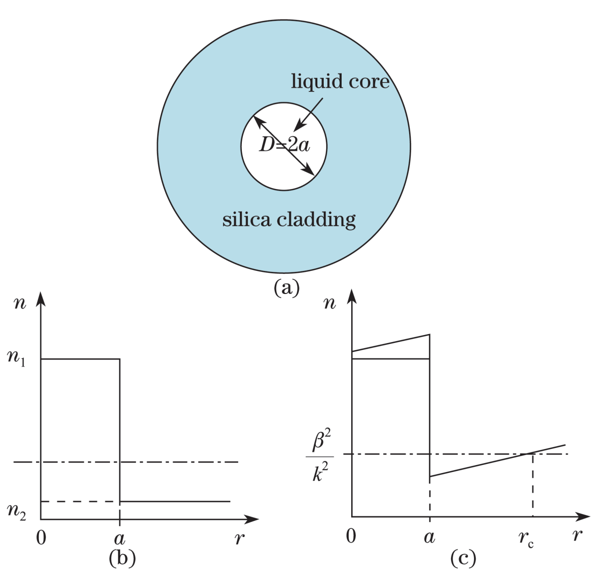

Fig. 1. Theoretical model of simulation: (a) cross-sectional view of fiber, (b) refractive index distribution of the straight fiber, and (c) refractive index distribution of the bent fiber.

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index in some region ($r \geq r_c$) shown in Fig. 1(c) and the propagating mode becomes leaky. But it is possible to choose core material with appropriate high refractive index to increase the effective propagating refractive index to reduce or even eliminate the bending induced loss.

Based on the discussions above, we use the liquid-core fiber to fulfill the low bending loss requirement. We choose a mixture of two different liquids (toluene and chloroform) as the core material while keeping the silica cladding. The refractive index of our fiber materials as a function of wavelength at 20 °C can be found in Refs. [24,25] as

$$n_{\text{tolu}}(\lambda) = 1.474775 + \frac{0.699031 \times 10^{-2}}{\lambda^2} + \frac{2.1776 \times 10^{-4}}{\lambda^4}, \quad (1)$$

$$n_{\text{chlo}} = 1.431364 + \frac{0.563241 \times 10^{-2}}{\lambda^2} - \frac{2.0805 \times 10^{-4}}{\lambda^4} + \frac{1.2613 \times 10^{-5}}{\lambda^6}, \quad (2)$$

$$n_{\text{silica}}^2 = 1 + \frac{0.6961663\lambda^2}{\lambda^2 - (0.0684043)^2} + \frac{0.4079426\lambda^2}{\lambda^2 - (0.1162414)^2} + \frac{0.8974794\lambda^2}{\lambda^2 - (9.896161)^2}. \quad (3)$$

At a given pressure and temperature T, the refractive index of the liquid mixture can be approximately expressed as a linear function of the concentration of toluene in the mixture ρ:

$$n_{\text{mixture}} = \left[n_{\text{tolu}}\Big|_{T=20\ ^\circ\text{C}} + \frac{\mathrm{d}n_{\text{tolu}}}{\mathrm{d}T} \times (T-20) \right] \times \rho + \left[n_{\text{chol}}\Big|_{T=20\ ^\circ\text{C}} + \frac{\mathrm{d}n_{\text{chol}}}{\mathrm{d}T} \times (T-20) \right] \times \Big(1-\rho\Big), \quad (4)$$

where $\mathrm{d}n_{\text{tolu}}/\mathrm{d}T = -5.273\times10^{-4}$ and $\mathrm{d}n_{\text{chol}}/\mathrm{d}T = -6.328\times10^{-4}$ are the thermal coefficients of the refractive indices[26]. While for the silica cladding, $\mathrm{d}n_{\text{silica}}/\mathrm{d}T$ of about -4×10^{-6} can be neglected compared with the liquids. The refractive index of germanium-doped core of conventional fiber can be found as [27]

$$\frac{n_c^2 - 1}{n_c^2 + 2} = \sum_{i=1}^{3} \frac{(A_i + B_i f)\lambda^2}{\lambda^2 - z_i^2}, \quad (5)$$

where $A_1 = 0.2045154578$, $A_2 = 0.06451676258$, $A_3 = 0.1311583151$, $B_1 = -0.1011783769$, $B_2 = 0.1778934999$, $B_3 = -0.1064179581$, $z_1 = 0.06130807320\ \mu$m, $z_2 = 0.1108859848\ \mu$m, $z_3 = 8.964441861\ \mu$m, and we assume the doping concentration $f = 0.09$.

As is known, the high order modes are more prone to leak than the fundamental mode in a bent fiber, thus the study of the single mode condition becomes crucial. This condition can be obtained by $V = \pi\left(n_1^2 - n_2^2\right)^{1/2} D/\lambda_0 < 2.405$, where D and λ_0 are the core diameter of fiber and light wavelength, respectively. To realize the tunable property of the liquid-core fiber, we attempt to get the single mode condition under different temperatures, as shown in Fig. 2. The single mode condition of the fiber is the region below the solid line.

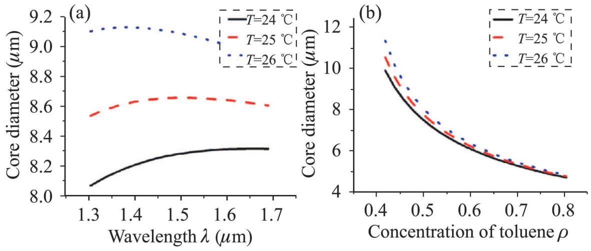

Fig. 2. Single mode condition of the liquid-core fiber at different temperatures with (a) the concentration of toluene of 45% and (b) the wavelength of 1550 nm.

Figure 2(a) describes the fiber core diameter required for single mode propagation as a function of wavelength, when the concentration of toluene is 45% and the temperature is around 25 °C. Figure 2(b) describes the core diameter as a function of the concentration of toluene when the wavelength is 1550 nm around 25 °C. We can find from Fig. 2(a) that the single mode property is maintained under small wavelength variation in the communication band, and from Fig. 2(b) that the property is maintained when the concentration of toluene is below 46%. So it is reasonable for us to restrict our simulation under single mode propagating condition. In our following text, we assume the concentration of toluene in the mixture to be 45%, which means that the refractive index difference between core and cladding is $n_{\text{core}} - n_{\text{clading}} = 0.0065$ at 25 °C.

The bending loss of a fiber can be expressed as $L_s = 10\log\left[\exp(2\alpha L)\right]$, where L is the fiber length and α is the loss coefficient determined by the fiber structure, bent radius, and wavelength[28]: $\alpha = T\exp\left(2Wa - 2W^2R/3\beta^2\right)\Big/2\sqrt{R}$ for the fundamental mode, where $T = 2ak^2\Big/2\sqrt{\pi W}V^2, k^2 = n_1^2k_0^2 - \beta^2, W^2 = \beta^2 - n_2^2k_0^2, V^2 = a^2k_0^2\left(n_1^2 - n_2^2\right)$, β is the propagation constant, R is the bent radius, and a is the core radius of the fiber.

We obtain the bending loss of the liquid-core fiber at 25 °C as well as that of conventional single mode fiber as a function of the bent radius at the wavelength of 1550 nm in Fig. 3. It is clear to see that the liquid-core fiber can be bent into much smaller radius than conventional fiber. In order to understand this advantage better we

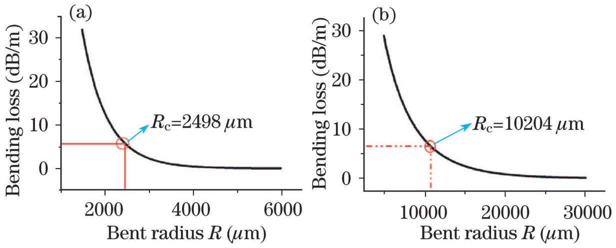

Fig. 3. Bending loss of (a) the liquid core fiber and (b) conventional single mode fiber.

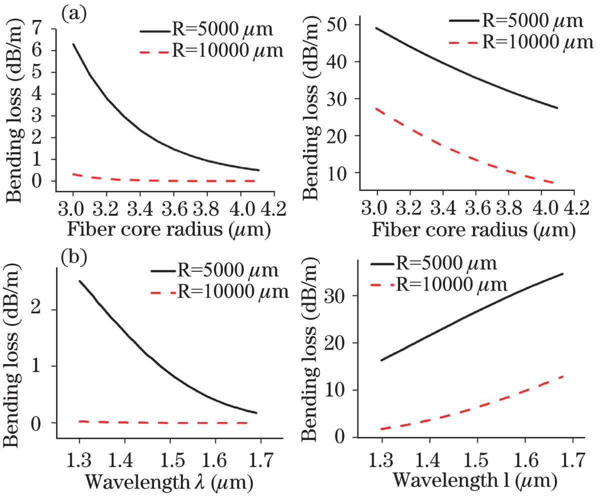

Fig. 4. Bending loss varies with the fiber core radius and wavelength for liquid core fiber (left) and conventional single mode fiber (right).

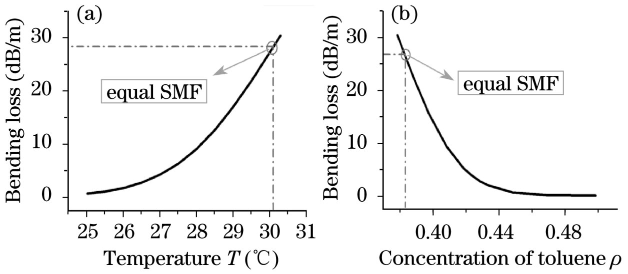

Fig. 5. Bending loss of liquid core fiber as a function of (a) the temperature T and (b) the concentration of toluene ρ.

introduce the critical bent radius below which the bending loss becomes significantly large and increases exponentially with bent radius[29]. This critical radius can be obtained from the loss equation as $R_c = 3\beta^2(0.347 + 2Wa)/2W^3$ which is also identified in Fig. 3.

From Fig. 3, we find that the critical bent radius of the liquid-core fiber is smaller than 5000 μm, almost one magnitude smaller than that of the conventional single mode fiber. We also compare the loss of the two kinds of fiber at a fixed bent radius of 5000 μm, 0.089 dB/m for the liquid-core fiber while 27 dB/m for conventional single mode fiber. Moreover, the bending loss of liquid-core fiber can be reduced further by increasing the concentration of toluene or decreasing the temperature.

In addition, we calculate the bending loss versus the fiber core radius and wavelength for both the liquid-core fiber and conventional fiber as depicted in Fig. 4. For both kinds of fiber, the bending loss increases with a decreasing fiber core radius. Meanwhile, the bending loss of conventional single mode fiber increases while that of liquid-core fiber decreases with larger wavelength. This trend is reasonable as the refractive index difference of liquid core fiber between liquid core and silica cladding increases much faster with increasing wavelength than that of conventional single mode fiber, which leads to stronger confinement of light in fiber core even at larger wavelengths. Above all, we can find that the bending loss of liquid-core fiber is about one magnitude smaller than that of the conventional fiber under every condition.

As mentioned before, the refractive index of liquid-core is dependant on temperature and mixture ratio. Here, we take these effects into account. The tunable property of bending loss of the liquid-core fiber is depicted in Figs. 5(a) and (b), which are both obtained at the wavelength of 1550 nm and a bent radius of 5 mm. The concentration of toluene is 45% for Fig. 5(a) and the temperature is 25 °C for Fig. 5(b). The marked points in Fig. 5 are where the bending loss of liquid-core fiber equals that of the conventional fiber. From Fig. 5, we know that the bending loss increases with the increasing temperature but decreases with the increasing concentration of toluene. The bending loss of liquid-core fiber is smaller than conventional single mode fiber when the temperature is below 30 °C at the toluene concentration of 45%, and it can be tuned even smaller by the liquid mixture ratio. When the temperature gets higher, the bending loss of liquid-core fiber will be larger than that of the conventional fiber at a toluene concentration of 45% as illustrated in Fig. 5(a). But we can change the liquid mixture ratio to reduce the loss to a relatively small range in this situation. This tunable property of liquid-core fiber may prove its potential uses in sensing and attenuation.

In conclusion, we have proposed the liquid-core optical fiber as a bending insensitive fiber with bending loss less than 0.1 dB/m at a bent radius of 5000 μm. The bending loss of this fiber is two magnitudes smaller than that of the conventional single mode fiber at the bent radius of 5000 μm and almost suppressed at a bigger bent radius. By simulation, we prove that this fiber is also a single-mode fiber around communication band. Furthermore, such fiber's optical properties are both thermal dependent and concentration related, which make its bending loss tunable. We believe that this kind of fiber may find its potential applications in all-optical network.

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