Electrically driven motion of micro-fluids in air-silica microstructure fiber: application to tunable filter/attenuator

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Abstract: We present an approach for manipulating light in an optical fiber where efficient modal field interaction is achieved between modes propagating in an air-silica microstructure optical fiber and micro-fluids incorporated in the air-holes of the fiber. We demonstrate this apporach in terms of applications to tunable devices.

1. Introduction

Air-silica microstructure fibers (ASMF) are attracting current interest because of their unique optical properties and ability to manipulate light. These fibers are typically all-silica optical fibers with air-holes introduced in the cladding region that run along the length of the fiber [1]. The distribution as well as the size of the air-holes can be designed to change the optical properties in the transmission of these fibers. For example, light can be guided by a photonic bandgap [2], or propagate as an endlessly single mode [3], or experience a regime of enhanced non-linearity [4].

In this paper we demonstrate simple principle for the manipulation of light propagating in ASMFs by achieving efficient interaction between the optical field and fluids pumped and positioned in the air-holes (channels) of the fiber. We introduce for this purpose two approaches (methods for attaining interaction between light propagating in the fiber and the fluids). First, a long period grating (LPG) is written in the core of the fiber, which couples the core mode into a mode whose field distribution is in the cladding and hence is sensitive to the index change in the air-holes. A second approach is tapering the fiber into small diameter size where the mode field leaves the core and spreads into the cladding to extend into the silica/air-holes interface. In addition, tunability is obtained by actively controlling the motion and position of fluids by thermal expansion of air in the channels using capillary tube heaters [5]. This will enable the fluid to move in the channels along the fiber to a position where overlap with the optical fields can be attained.

2. Electrically driven micro-fluidics

Fig.1(a) shows a scanning electron micrograph of the ASMF, which is comprised of six approximately cylindrical air-holes introduced in the cladding. These air-holes form an inner cladding region of ~34μm in diameter and are large enough to allow for the infusion of micro-fluids, as shown in Fig.1(b), and be positioned at desired spots in the fiber. The core is germanium doped of diameter ~8μm, the outer diameter is 125μm, and $\Delta = (n_1 - n_2)/n_1$ ~0.35%, where n_1 and n_2 are the refractive indices of the germanium core and silica, respectively [6].

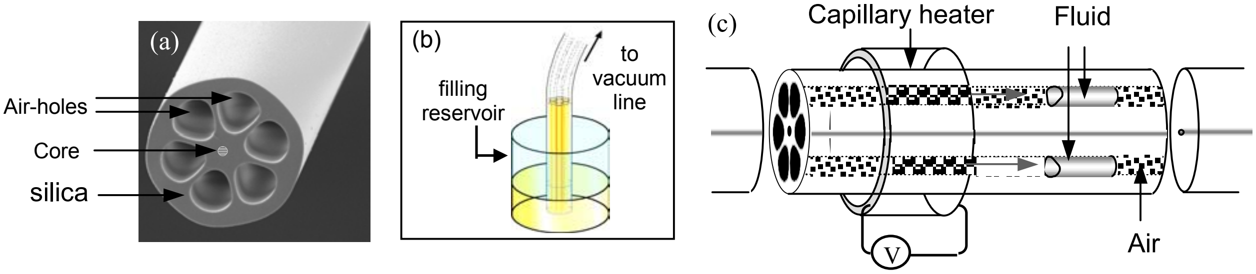

Fig. 1 (a) Scanning electron micrograph of the ASMF. (b) Filling of the fluid into the air-channels of the ASMF. (c) Moving the fluid in the air-channels of the ASMF by sealing the channels and applying heat to one side of the channel.

The principle of displacing the fluid along the air-channels is demonstrated in Fig. 1(c). The ASMF is spliced to a conventional single mode fiber (SMF), which provides light coupling to the core as well as a hermetic seal for the channels. A capillary heater is used to thermally expand the air in the channels, which induces pressure on one side of the fluid plug. This will result in pushing the micro-fluid in the desired direction. When the heater is deactivated, pressure from the opposing air segment drives the fluid to its original equilibrium position.

3. Grating based approach

A LPG, which is periodic perturbation in the index of the core with periodicity of Λ~500µm, is written in the core of the fiber. Light propagating in the core incident on the grating will couple to forward propagating higher order modes in the cladding region, which satisfying the phase matching conditions expressed in term of resonance wavelengths:

$$\lambda_{clad,i} = (n_{core} - n_{clad,i})\Lambda \qquad (1)$$

where $\lambda_{clad,i}$, $n_{clad,i}$, and n_{core}, are the resonance wavelength, the effective index the ith cladding mode, and effective index of the core mode, respectively. Coupling to these "cladding" modes manifests as sharp resonance loss in the transmission spectrum of the fiber as shown in Fig.2(a). The core mode of the fiber is not affected by the presence of the air holes or materials infused in them [7]. On the other hand, cladding modes have their energy field distribution spread into the cladding and are sensitive to any change in the refractive index at the cladding air-hole interface. Therefore, efficient interaction between the mode field and active materials infused in the air-holes is enabled.

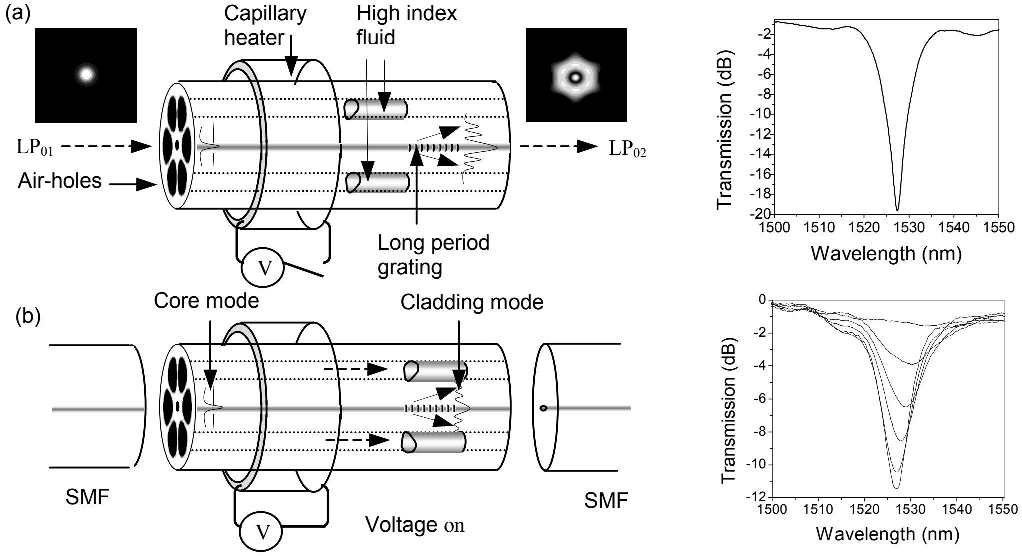

Fig.2 Schematic diagram of the ASMF with (a) high index fluid in the holes away from the grating when no voltage is applied. (b) fluid is pushed towards the grating when voltage is on where overlap with the cladding mode is enabled.

When the segment of fluid is far from the grating, as shown in Fig. 2(a), the cladding mode (LP_{02}) coupled by the grating is not affected by the fluid. To control the motion of fluid, a capillary tube, which is located 10 cm away from the fluid, heats the air in the channels to about 140°C. These will induce pressure on one side of the fluid and create a thermal gradient between the opposite sides of the fluid plug and result in pushing the fluid along the channel towards the grating, as shown in Fig.2(b). The overlap of the cladding mode with a high index material will affect the guidance mechanism of the mode [7], which experiences refraction into the high index and becomes a leaky mode. Fig. 2(b) shows the transmission of the fiber as the liquid shifts onto the grating region and causes the resonance peak to decrease in strength.

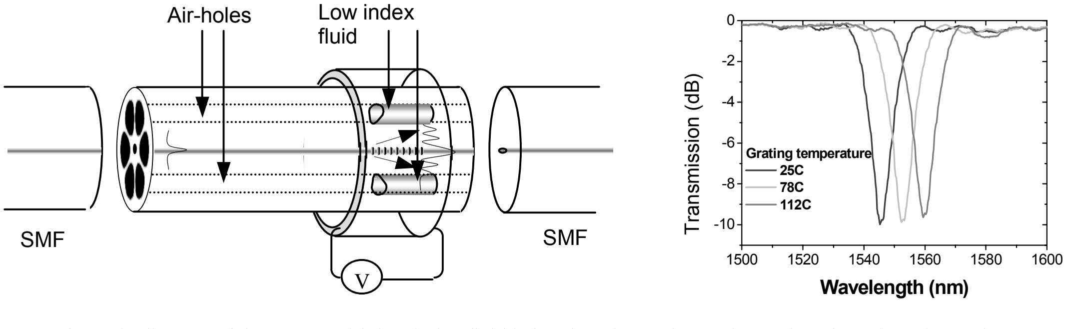

Fig. 3 Schematic diagram of the ASMF with low index fluid infused on the grating region. When the voltage is on, the refractive index of the fluid decreases and results in shifting the wavelength resonance.

In the case where the index of the fluid is lower than that of silica (n=1.3), the cladding mode will still be guided by total internal reflection. However, the effective index of the cladding mode ($n_{clad,i} = n_{02}$) will be sensitive to the variation in the refractive index of the fluid. Therefore, heating the fluid in the grating region will change the refractive index of the fluid, whose temperature dependence is dn/dT ~- 10^{-4}/°C. As a result, the wavelength at which the resonance occur, which is also dependent on the refractive indices and especially on ($n_{clad,i}$) as exhibited in Eq.1, will be shifted to higher wavelength, as shown in Fig. 3.

3. Taper based approach

Another method to obtain mode field interaction with the fluid is by adiabatically tapering the fiber [8]. The fiber is heated and stretched such that the fiber diameter is reduced while preserving its cross section index profile along the taper. If the fiber is decreased to very small diameter size, the core also reduces to a point where it does not support light. In this case, the mode field spreads into the cladding where its guidance depends on the cladding/air-holes interface. In the case where the fluid is in the non-tapered region, Fig. 4(a), the mode in the core is unaffected by the air-holes. In the tapered region (waist), it is also guided by total internal reflection because the refractive index of air is lower than that of silica and propagates back into the core with loss lower than 0.1 dB[9]. Fig. 4(a) shows a tapered ASMF to 50μm in outer diameter and the length of the waist is 1cm long. By heating the air channels, which are sealed on both sides, with a capillary tube, pressure will build up and the fluid (n=1.8) will be pushed into the waist of the fiber. This will result in changing the boundary conditions at the channel/fluid interface. Hence, the mode field will not experience total internal reflection, but will be refracted into the high index material. Light then is lost into the channels and cannot be transmitted along the fiber (Fig. 4(b)). In which case, this system behaves as a broadband attenuator with a switching speed of about 10 seconds.

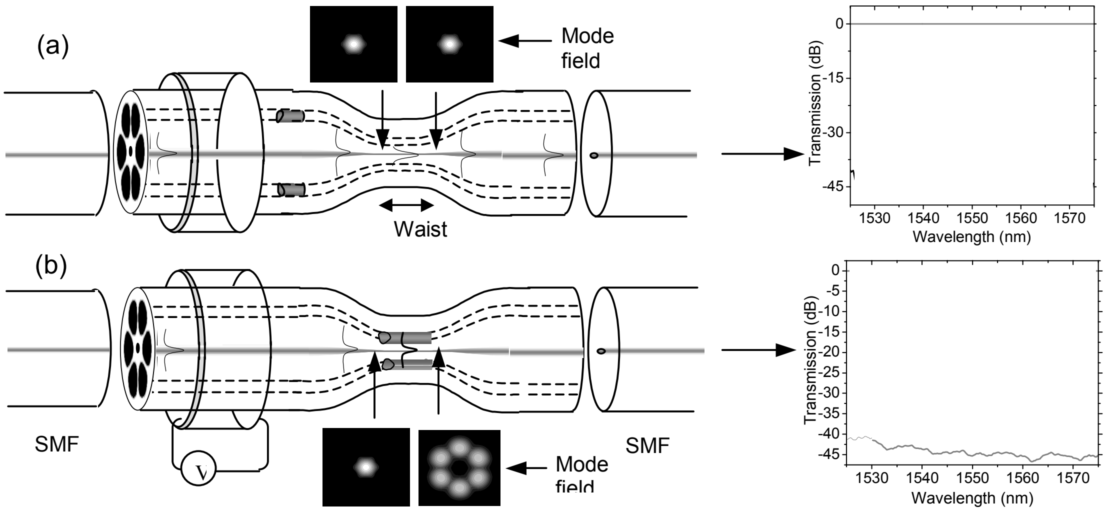

Fig.4 Tapered ASMF to 50μm (a) with fluid away from the taper and no effect on the propagating mode (b) fluid in the waist of the fiber where light is lost due to refraction into the high index material. The mode

4. Conclusion

In conclusion, we demonstrate that positioning of fluids along micro-capillary channels inside the fiber enables the manipulation of light at narrow or large bandwidths. This approach uses low voltages, and can be applied to different fluids. In addition, it has the potential for changing the modal properties of light in fibers in a way that cannot be achieved in other conventional fibers. The motion (magnitude and direction) of the fluid is controlled the amount of pressure or heat delivered by capillary heaters.

5. References

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