Suspended twin-core fiber for optical switching

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A kind of novel fiber, comprising two fiber cores which are suspended in air inside the outer cladding via a central thin membrane, is proposed for optical switching application. When a hydrostatic pressure applied on the optical fiber, the pressure-induced refractive index change of the two fiber cores will contribute to the periodical change of the intensity of guided light in the fiber core. The mode coupling of two cores under different hydrostatic pressure and influences of each structure parameter of the proposed fiber on the switching pressure have been numerically investigated.

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Since the invention of the first low-loss single mode fiber in 1970, incredible progress in optical fiber fabrication techniques and processes has been seen in the last decades, especially after the emergence of the microstructured optical fiber. A lot of theoretical and experimental research works which aimed at meeting the need of particular function (e.g. as high birefringence[1−3], flattened dispersion[4], large negative dispersion[5−7], high nonlinearity[8], endless single mode[9] and so on) have been carried out, resulting in the realization of an increasing number of novel fibers. Recently, a nanomechanical twin-nanoweb fiber in which each fiber core is held suspended in air from the outer glass cladding by two glass membranes has been fabricated[10]. Based on such a twin-nanoweb fiber, different from the early reported dual-core photonic crystal fiber for hydrostatic pressure sensing[11], another important application, the optical switching[12] can be achieved. As an important supporting technology of optical communication systems, optical switching is taken account for the key-enabling function for the deployment of the developing all-optical networks. The incorporation of switching function into the optical fiber offer great promise for all-optical communication. However, in order to achieve the optical switching function, the twin-nanoweb fiber mentioned above has to be processed with chemical etching, which makes the fiber not convenient to use.

In this letter, we proposed a kind of suspended twin-core fiber (STCF) based on a single nanoweb structure for optical switching. The fiber has two cores which locate symmetrically in the center of the nanoweb, resulting to the mode coupling for the guiding light in the STCF. When a hydrostatic pressure applied on the optical fiber, the pressure-induced refractive index change will contribute to the intensity of core-guided mode change periodically with pressure. Compared to the twin-nanoweb fiber, the fiber we proposed only incorporates a single membrane which makes it easier to be fabricated. Besides, the STCF can be directly used for switching application without post processing. The influences of each structure parameter on the switching pressure are presented.

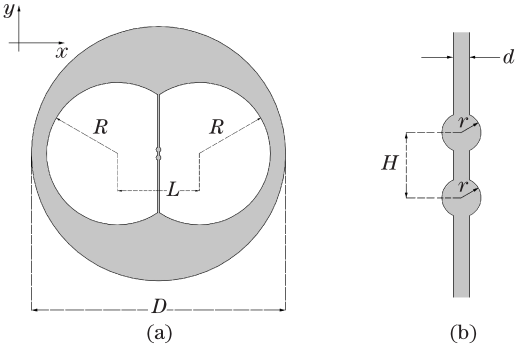
Figure 1 shows the cross-section of the proposed fiber. The external diameter of the fiber is D, which is kept being a constant of 125 μm in this letter. A pair of large air holes with a radius R is employed in the cross-section. The distance between the center of two air holes is L, which is smaller than $2R$. A thin membrane (so-called single nanoweb) with thickness d locates in the intersection area of the two air holes. Two fiber cores with diameter of r locate symmetrically in the center of the nanoweb. The distance of the two cores is H. A full-vector finite-element method (FEM) is used to investigate the mechanical properties and guided modes of the proposed STCF.

When a hydrostatic pressure is applied on the optical fiber, the pressure-induced refractive index change and the pressure-induced structure deformation will affect the light guiding in the optical fiber[13,14].

$$n_x = n_0 - C_1\sigma_x - C_2\left(\sigma_y + \sigma_z\right), \tag{1}$$

$$n_y = n_0 - C_1\sigma_y - C_2\left(\sigma_x + \sigma_z\right), \tag{2}$$

$$n_z = n_0 - C_1\sigma_z - C_2\left(\sigma_x + \sigma_y\right). \tag{3}$$



(a) (b)

Fig. 1. (a) Cross-section of the proposed STCF. (b) Enlarged view of the twin-core region of the proposed STCF.

And the pressure-induced refractive index change are

$$\Delta n_x = n_x - n_0 = -C_1\sigma_x - C_2\left(\sigma_y + \sigma_z\right), \quad (4)$$

$$\Delta n_y = n_y - n_0 = -C_1\sigma_y - C_2\left(\sigma_x + \sigma_z\right), \quad (5)$$

$$\Delta n_z = n_z - n_0 = -C_1\sigma_z - C_2\left(\sigma_x + \sigma_y\right), \quad (6)$$

where σ_x, σ_y and σ_z are the stress components, $C_1 = 6.5 \times 10^{-13}\text{m}^2/\text{N}$ and $C_2 = 4.2 \times 10^{-12}\text{m}^2/\text{N}$ are the stress-optic coefficients of pure silica. Since z-direction almost makes no difference to the polarized mode of the optical fiber, we usually use the 2-dimension analyze based on the FEM for the cross-section of the optical fiber to achieve the pressure-induced refractive index change. Considering a STCF with parameters of $R = 35$ μm, $L = 40$ μm, $d = 1$ μm, $H = 3$ μm and $r = 1$ μm under the hydrostatic pressure of 1 MPa, the σ_y shown in Fig. 2(a) can be calculated by using the plane stress model. The negative stress component means compressive stress. Note that the calculated σ_x is much smaller than σ_y in the twin-core region and it is zero in the rest part of the nanoweb, thus it is ignored for the calculations of the pressure-induced index change. The amplification effect of the proposed structure is obvious, a pressure of 1 MPa applied to the STCF results in a high pressure up to about 17.15 MPa in the nanoweb of the STCF. According to Eqs. (4) and (5), we can have the distribution of the pressure-induced refractive index change along the y direction, which is shown in Fig. 2(b). In the center of the fiber cores, the pressure-induced index change is $\Delta n_x = 55.65 \times 10^{-6}$ and $\Delta n_y = 8.61 \times 10^{-6}$, respectively, which shows that the x-polarized light has a stronger response to the pressure applied to the STCF.

To investigate how the pressure-induced refractive index change influences the guiding light in the proposed STCF, we simulate the guiding modes in the twin-core region. Figure 3 shows mode profiles of the electric field and the normalized electric field distribution of x-polarized light along the y direction for (a) the even mode and (b) the odd mode. Note that, a STCF with parameters of $R = 35$ μm, $L = 40$ μm, $d = 1$ μm, $H = 3$ μm, $r = 1$ μm is employed and the operation wavelength λ is 1550 nm.

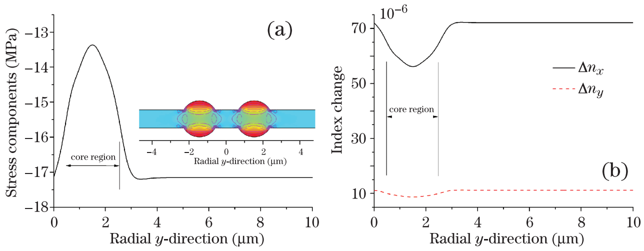


Fig. 2. (a) Distribution of the principal stress components of σ_y under the hydrostatic pressure of 1 MPa and (b) pressure-induced refractive index change (Δn_x and Δn_y in the radial y-direction) of the STCF with parameters of $R = 35$ μm, $L = 40$ μm, $d = 1$ μm, $H = 3$ μm, and $r = 1$ μm.

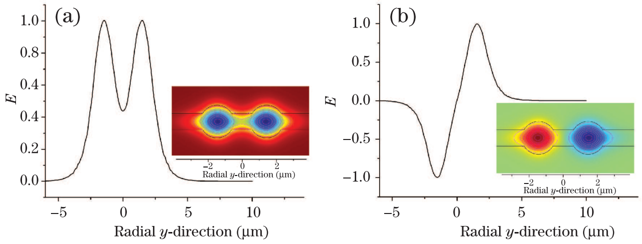


Fig. 3. Mode profiles and electric field distribution of x-polarized light along the radial y-direction for (a) the even mode and (b) the odd mode of the STCF at the wavelength of 1550 nm.

According to the mode coupling theory, the optic power transferred from one fiber core to the other fiber core after a length Z along the STCF is given by[15]

$$\begin{aligned} p(\lambda, Z) &= \sin^2(\left|n_\text{e} - n_\text{o}\right| Z \cdot \pi/\lambda) \\ &= \sin^2(\Delta n_\text{eo} Z \cdot \pi/\lambda), \end{aligned} \quad (7)$$

where $n_\text{e}(n_\text{o})$ is the effective refractive index of the even (odd) mode, $\Delta n_\text{eo} = n_\text{e} - n_\text{o}$. And the coupling length L_c is given by[15]

$$L_\text{c} = \lambda / \left(2\left|n_\text{e} - n_\text{o}\right|\right). \quad (8)$$

According to Eqs. (7) and (8), we can get a function of the optical transmittivity dependent on Z and L_c:

$$p(Z, L_\text{c}) = \sin^2(Z \cdot \pi/2L_\text{c}). \quad (9)$$

When the x-polarized laser light with the wavelength of 1550 nm is injected into one fiber core of the STCF without applied pressure, we can calculate transmission from another fiber core of the STCF according to Eq. (9). Figure 4(a) shows transmittivity of the x-polarized light when the length of the STCF is in the range around 20 cm. We can find that after only 0.22 mm, the optical power will be entirely transferred from one fiber core to the other. Therefore we can use the length of its integer times to initialize the optical switching device. Figure 4(b) shows the (x-polarized) transmission spectrum of the STCF with the length of 20.033 cm and 30.019 cm at pressure range from 0 to 60 MPa. Here, we define a switching pressure (ΔP) that is a pressure applied to the STCF to switch guided light from one fiber core to the other. We can clearly see that for the STCF with same structure parameters, longer the fiber is, smaller the switching pressure is needed, in the case of the incident light with a fixed wavelength. And the switching pressure of the STCF with the length of 20.033 cm is 24 MPa.

For practical application, the influences of each structure parameter on the switching pressure should be investigated. Firstly, we consider the effect of parameter R and L, both of which determine the proportion of air area in the cross-section of the fiber. Note that, in the following discussions, a 20-cm STCF with parameters of $R = 35$ μm, $L = 40$ μm, $d = 1$ μm, $r = 1$ μm and $H = 3$ μm is used as the reference for which ΔP of 24 MPa is needed to achieve optical switching. Changing the radius R when other parameters are fixed, we can have the relationship between the switching pressure and the radius R, which is shown in Fig. 5(a). The situation for L is similar and the relationship is shown in Fig. 5(b). It is easy to draw the conclusion that a STCF with a larger radius R or longer L would have a smaller switching pressure. This can be understood due to the fact that larger R or longer L would increase the proportion

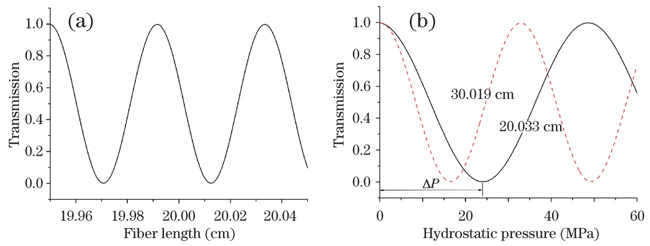


Fig. 4. (Color online) (a) Distribution of transmittivity along the length of the STCF with parameters of R = 35 μm, L = 40 μm, d = 1 μm, H = 3 μm, and r = 1 μm. (b) Transmission spectrum of a STCF with a length of 20.033 cm (black solid line) and 30.019 cm (red dotted line).

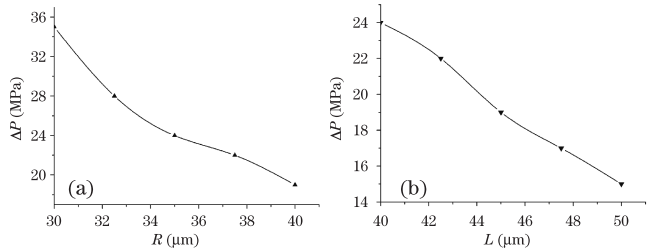


Fig. 5. Switching pressure for different values of (a) air hole radius R and (b) air hole distance L.

of air area in the cross-section of the fiber, which makes the fiber more sensitive to the applied pressure. The principle is similar with the special MSFs[16] with side holes which provide an internal amplification mechanism to enhance the pressure sensitivity. To obtain a STCF with smaller switching pressure, a larger value of R or L is desired based on the requirement of physical strength of the fiber.

Next, the thickness of nanoweb has been investigated. Figure 6 shows the switching pressure ΔP for a 20-cm STCF with different thickness d of the nanoweb when other parameters are fixed. In the calculated range, the switching pressure decreases when the thickness of nanoweb increase. This is mainly because the thin nanoweb will lead to a weak mode coupling of the twin cores since there is more air instead of silica material between the twin cores. Besides, although a thin nanoweb will improve the amplification effect on the applied pressure at the nanoweb region, the pressure change in the core region is very little in our calculated range. Based on this point, a thicker nanoweb is preferred to achieve a smaller switching pressure, but the confinement of the core-guided mode will become weak at the same time. Thus, a suitable value of d should be chosen for practical applications.

Then, the influence of core distance H was studied. Figure 7(a) shows that optical switching will be more difficult when the distance of the twin cores is widening, that is due to the fact that the larger distance H results in weak mode coupling between the twin cores.

The size of fiber cores also influences the property of the STCF for optical switching. Figure 7(b) shows the relationship between the switching pressure and the radius r when other parameters are fixed. We can find that there is a maximum value for ΔP in the calculated range. A lager r will enhance the mode overlapping of the twin cores since they are more close to each other, which is equivalent to the effect of reducing the distance H. While the fiber core with a small r will result to weak confinement of the mode light, and also strong mode coupling of the twin cores. This is equivalent to the effect of increasing the thickness d of nanoweb. Thus we need to consider the light confinement and sensitivity for optical switching together as a whole to achieve a suitable value of r in practical application.

Considering the practical application for optical switching, the proposed STCF shows several advantages compared to the early reported twin-nanoweb fiber[10]. The STCF only incorporates a single membrane which makes it easier to be fabricated, such as easily controlling the size of the twin cores and the distance between them. Besides, the STCF can be directly used for switching application without post processing, but the nanomechanical fiber should etch a portion of the cladding which broken the fiber structure and limits its mass production. We can easily apply pressure on STCF with relatively long length (up to several meters to achieve small switching pressure). Additionally, for the proposed STCF, optical switching is achieved based on the pressure-induced index change which essentially has advantages such as high response speed and high repeatability[17], compared with optical switch based on mechanical movement of the twin-nanoweb fiber. Of course, further research work is needed to achieve a smaller switching pressure, which will contribute to a small size of a packaging device based on the proposed STCF. A smaller switching pressure will also ensure smaller pressure-induced structure deformation of the STCF to avoid nanoweb bending in the x-direction. It is also valuable to mention that the practical fabrication of the STCF may result in the size different of the two fiber cores, which will result in the low extinction ratio for optical light switching.

In conclusion, a STCF has been introduced and proposed for optical switching application in this letter. Optical and mechanical properties of the proposed STCFs

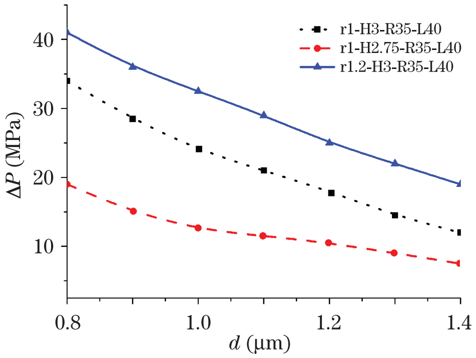


Fig. 6. Switching pressure for different values of d.

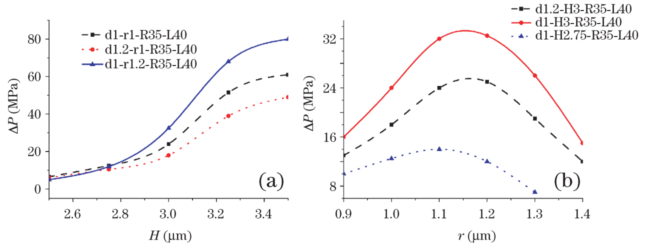


Fig. 7. Switching pressure for different values of (a) core pitch H and (b) core radius r.

under different pressure have been numerically investigated. The influences of each structure parameter on the switching pressure have been presented and the optimized method for achieving a fiber with low switching pressure has been indicated. Finally, we present a discussion on the advantages of the proposed STCF compared with the early reported twin-nanoweb fiber, the fabrication influence and the further research work for the proposed STCF.

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