Determination of the wavelength dependence of the coupling effect in twin-core microstructured polymer optical fibers

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Abstract. A simple and straightforward method is applied to experimentally obtain the wavelength dependence of the intercore beat length for two different types of twin-core microstructured polymer optical fiber. The results are compared with numerical calculations using a full-vectorial plane-wave expansion method, which shows good agreement. [DOI: 10.1117/1.2751137]

Subject terms: microstructured optical fiber; polymer fiber; beat length; coupling coefficient.

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1 Introduction

Since the first single-material optical fiber was demonstrated in the 1970s,[1] microstructured optical fiber (MOF) has attracted much research interest worldwide.[2] Taking advantage of the air holes in the fiber cladding, the microstructure has been incorporated in many fiber devices based on mode coupling, such as long-period gratings,[3] fiber Bragg gratings,[4] fused couplers,[5] and multicore fibers.[6] Among these fiber devices, a multicore fiber can be obtained by using multiple solid rods as defects in the capillary stack-and-draw fabrication process. For twin-core MOF, much work has been done on the numerical calculation of beat lengths.[7–9] In Ref. 7, two designs of twin-core MOF were theoretically analyzed. However, the experimental confirmations remain sparse.[8,9] In Ref. 9, the wavelength dependence of the coupling effects could not be determined directly from the experiment. The incoherence of the white light source degrades the periodic pattern in the transmission spectrum. Therefore the measured results could only be used for point-by-point verification of the simulations. Furthermore, the fiber cores have a strong asymmetry, which is not desired for a twin-core fiber in general applications. In this paper, we determine the wavelength dependence of the coupling directly from the periodic output spectrum. At the same time, the relationship of the coupling coefficient, its dispersion, and structure parameters (air-filling fraction and core-to-core separation) is investigated both theoretically and experimentally.

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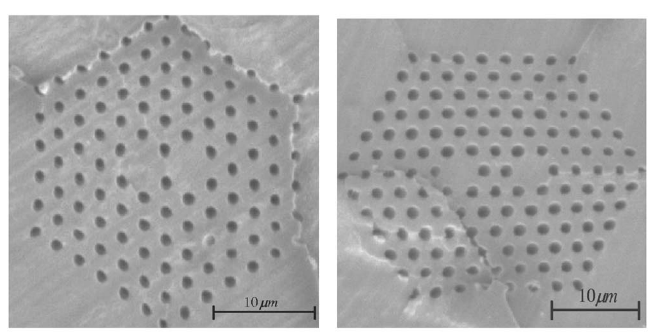
2 Theoretical Analysis of Supermodes in Twin-Core Microstructured Polymer Optical Fiber

In order to study the characteristics of coupling between the guided modes in a twin-core MOF, we have fabricated two types of twin-core microstructured polymer optical fibers (mPOFs) as shown in Fig. 1. Unlike silica MOFs, which are generally fabricated by stacking capillaries to form the microstructure, the pattern in an mPOF is drilled into a preform, followed by a fiber-drawing process.[10] After fabrication, the single-mode nature of the individual cores in the fibers was confirmed from a wavelength of 633 nm upward.[9]

In case of the twin-core mPOF structures as shown in



(a) (b)

Fig. 1 Scanning electron micrograph of twin-core microstructured polymer optical fiber (mPOF): (a) structure A: $\Lambda=2.3\ \mu\text{m}$, $d=0.8\ \mu\text{m}$, $S=\sqrt{3}\Lambda$; (b) structure B: $\Lambda=2.5\ \mu\text{m}$, $d=1.4\ \mu\text{m}$, $S=3\Lambda$.

Fig. 1, Λ is the hole-to-hole lattice distance, d is the air-hole diameter, and S is the separation between the centers of two cores. The light energy is expected to switch between the identical cores in a spatially periodic fashion. The refractive index of background polymer material (PMMA) is calculated from the Sellmeier equation

$$n^2 = A_1 - A_2\lambda^2 + \frac{A_3}{\lambda^2} - \frac{A_4}{\lambda^4} + \frac{A_5}{\lambda^6} - \frac{A_6}{\lambda^8},$$

where

$A_1 = 2.1864582,$

$A_2 = 2.4475348 \times 10^{-4}\ \mu\text{m}^{-2},$

$A_3 = 1.4155787 \times 10^{-2}\ \mu\text{m}^{2},$

$A_4 = 4.4329781 \times 10^{-4}\ \mu\text{m}^{4},$

$A_5 = 7.7664259 \times 10^{-5}\ \mu\text{m}^{6},$

$A_6 = 2.9936382 \times 10^{-6}\ \mu\text{m}^{8}.$

The ratio of d to Λ can be designed to be very large, providing a large air-filling fraction. The effective index of the microstructured cladding is a much stronger function of wavelength than for the case of a conventional fiber cladding with a homogeneous material index, so the twin-core waveguide is treated as a superstructure and the fundamental modes are obtained from a full-vectorial plane-wave expansion method (PWM).[11] We only present a simple case here: the two separate cores are identical, lossless, and monomode. Single-circular-core fiber has degenerate HE_{11}^x and HE_{11}^y modes. When we have two cores, the rotational symmetry of the twin core is broken. The x-polarized fundamental mode breaks into two modes: even HE_{11}^x and odd HE_{11}^x. When the two modes are in phase, the left core has almost zero energy due to destructive interference. Similarly, if the two modes are in antiphase, the right core has almost zero energy. The effective indices of four different modes are calculated for obtaining the beat length as shown in Fig. 2(a). It is obvious that the coupling coefficient is only slightly different for the x-polarized and y-polarized modes. So polarization effects are neglected in this study for simplicity. The beat length is obtained from the effective mode indices of one polarization:

$$L_c = \frac{\lambda}{n_e - n_o}, \tag{1}$$

where L_c is the beat length, and n_e and n_o are the effective indices of the even and odd modes, respectively. For a twin-core mPOF with air-hole spacing $\Lambda = 2.3\ \mu$m, air-hole diameter $d = 0.8\ \mu$m, and core-to-core distance $S = \sqrt{3}\Lambda$, which corresponds to the fiber structure in Fig. 1(a), the calculated indices of the two polarizations are almost indistinguishable. The calculated beat length for x-polarized and y-polarized modes is shown in Fig. 2(b). The beat length L_c has been shown to be of the form[9]

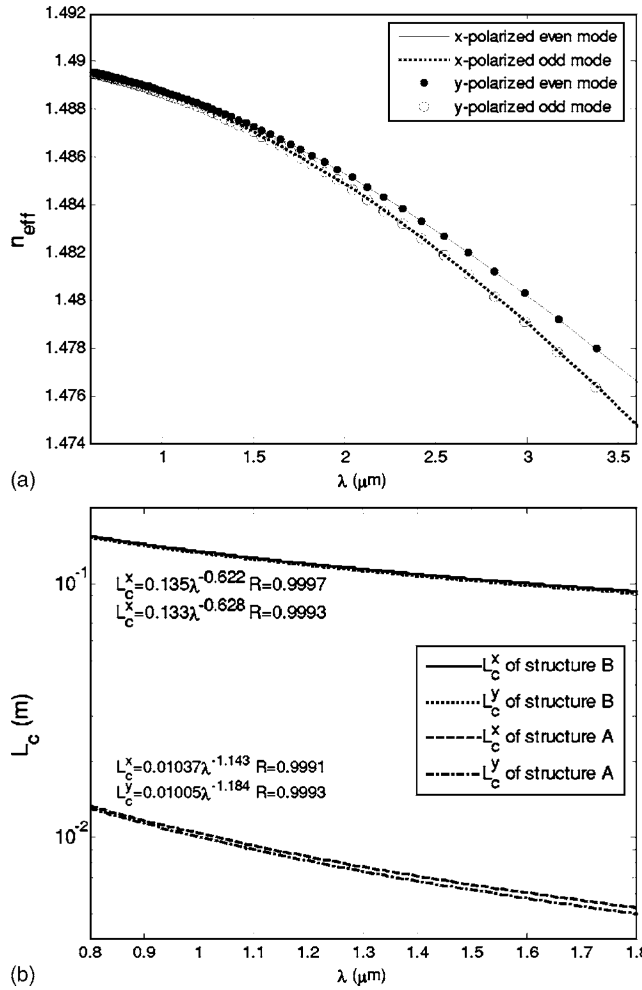


Fig. 2 (a) Effective indices of the four supermodes in structure A. (b) Theoretical L_c for both polarization modes of twin-core mPOF structures A and B.

$$L_c = C\lambda^{-\eta}, \tag{2}$$

where C and η are two constants. Fitting the power function to the calculated results in Fig. 2(b) confirms Eq. (2), and we find that for structure A the relationship between the beat length and wavelength is $L_c^x = 0.01037\lambda^{-1.143}$, $L_c^y = 0.01005\lambda^{-1.184}$ for the two polarizations. Similar wavelength dependent power functions were also calculated for structure B, and the results are shown in Fig. 2(b): $L_c^x = 0.135\lambda^{-0.622}$, $L_c^y = 0.133\lambda^{-0.628}$.

Comparing these calculations, we observed that the constant C for fiber A is one order larger than that for fiber B, and the coefficient η is decreased by nearly a factor of two. Clearly, the dramatic increase of the beat length for structure B is due to the larger separation of the two cores. By varying the air-hole size of structure A from 0.95 to 0.8 μm, the corresponding beat-length dependence on wavelength is found to be

$d = 0.95\ \mu\text{m}, \qquad L_c = 0.015\lambda^{-1.23},$

$d = 0.90\ \mu\text{m}, \qquad L_c = 0.013\lambda^{-1.15},$

$d=0.85\ \mu\text{m}, \qquad L_c=0.011\lambda^{-1.149},$

$d=0.80\ \mu\text{m}, \qquad L_c=0.010\lambda^{-1.143}.$

We found that the beat length decreases greatly with even small changes of air-hole size. The power factor η also decreases, which indicates that the wavelength dependence gets weaker with a decrease in air filling fraction. Since the beat length is inversely proportional to the coupling coefficient, we can conclude that for the same air-hole arrangement structure, there appears to be a trade-off between the coupling coefficient and its wavelength dependence. This trade-off is also observed between structure A and structure B but with same air-filling fractions, that is, d/Λ ratio. From the power function of wavelength dependence, this indicates the application of our twin-core fiber as a directional coupler.

3 Measurement of Beat Length

When light is launched into one core, because the beat length is defined as the required fiber length for achieving complete power transfer from one core to another and back, we have

$$L=NL_c(\lambda)=(N+1)L_c(\lambda+\Delta\lambda), \tag{3a}$$

where L is the fiber length, $N=L/L_c(\lambda)$ is a real number, and $\Delta\lambda$ is the wavelength spacing between adjacent minima in the transmission spectrum from one core at the end of the fiber. For $\Delta\lambda/\lambda \ll 1$,

$$L_c(\lambda+\Delta\lambda)\approx L_c(\lambda)+\Delta\lambda\cdot\frac{\mathrm{d}L_c(\lambda)}{\mathrm{d}\lambda}. \tag{3b}$$

From Eq. (2), we can derive

$$\frac{\mathrm{d}L_c(\lambda)}{\mathrm{d}\lambda}=-C\cdot\eta\cdot\frac{\lambda^{-\eta}}{\lambda}=-\eta\cdot\frac{L_c}{\lambda}. \tag{3c}$$

Substituting Eqs. (3b) and (3c) into Eq. (3a), we have

$$L=\left(\frac{L}{L_c}+1\right)\left[L_c+\Delta\lambda\cdot\frac{\mathrm{d}L_c(\lambda)}{\mathrm{d}\lambda}\right]$$

$$=L+L_c-\left(\Delta\lambda\cdot\eta\cdot\frac{L_c}{\lambda}\right)\left(\frac{L}{L_c}+1\right). \tag{3d}$$

Since $\Delta\lambda/\lambda \ll 1$ and $L/L_c \gg 1$, we can get the relationship between the beat length and the wavelength spacing:

$$\frac{L_c}{L}\approx\eta\cdot\frac{\Delta\lambda}{\lambda}. \tag{4}$$

Mathematically, the beat length L_c and the wavelength dependence factor η can be obtained with two different fiber lengths and the corresponding $\Delta\lambda$. Therefore, we may measure the beat length and the corresponding wavelength dependence by using a straightforward *cutback* method. A broadband white light source was launched into only one core of the twin-core fiber by butt coupling to a supercontinuum source, which consisted of a Nd:YAG microchip laser at 1064 nm (8.3 μJ and 0.56 ns per pulse, at 7.14-kHz repetition rate and 6-kW peak power, generating a broad supercontinuum from 400 to 1600 nm) coupled into a section of 20 m of highly nonlinear photonic crystal fiber (HNL PCF) from Crystal Fibers (SC-5.0-1040), with a 3.2-μm mode field diameter and a zero-dispersion wavelength of $\lambda_0=1040$ nm. At the output port of the twin-core fiber, the light from only one core was collected at an optical spectrum analyzer by imaging the fiber end face with a microscope objective and blocking the light from the other core with a razor blade.

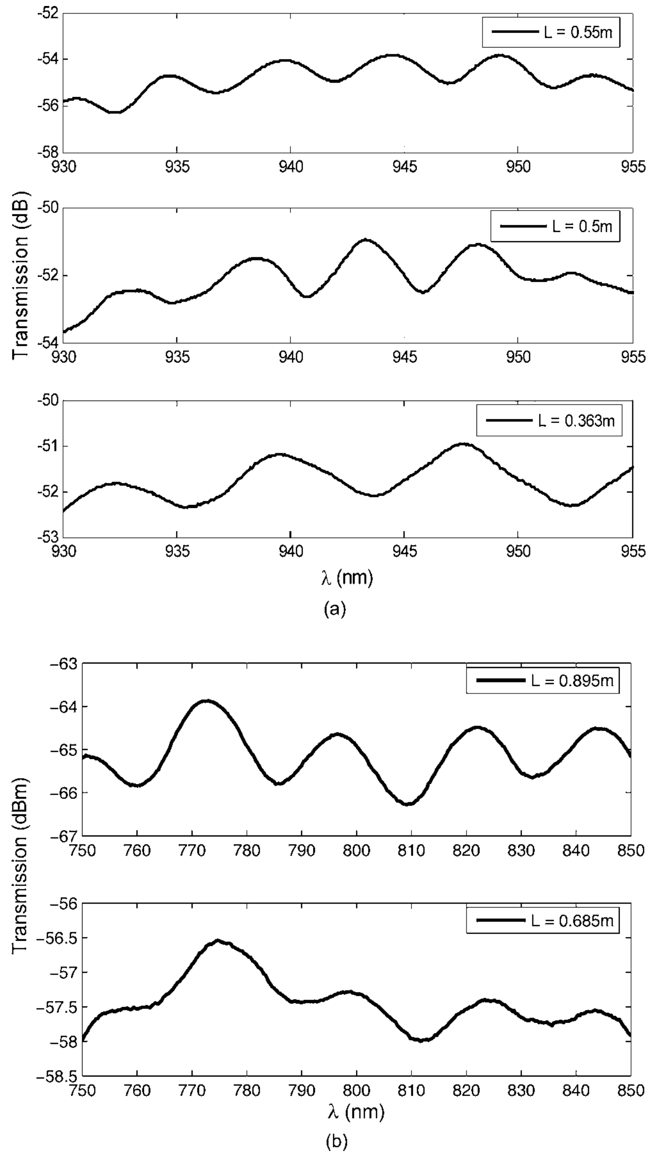


Fig. 3 Transmission spectrum from one of the two cores for mPOF: (a) structure A; (b) structure B, at different fiber lengths of the same fiber.

Theoretically, the polarization effects in the structure can be neglected, since the beat lengths for the x- and y-polarized modes are nearly identical for short wavelengths, as shown in Fig. 2. We have also tested the influence of polarization effects in the measurement by adding a polarizer before the light enters the highly nonlinear fiber.

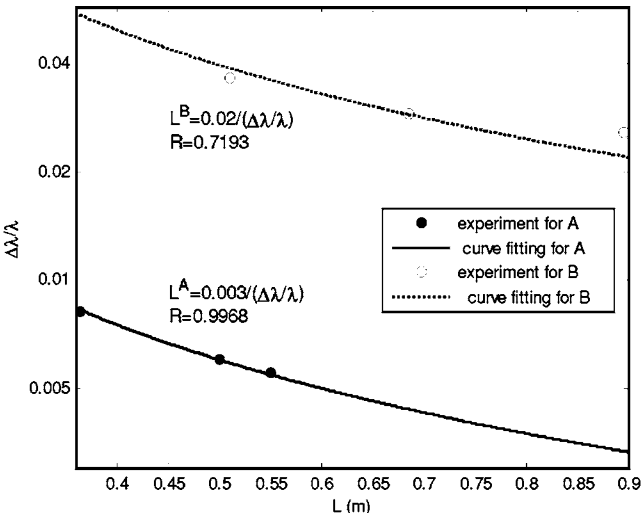


Fig. 4 Spacing-to-wavelength ratio $(\Delta\lambda/\lambda)$ is inversely proportional to fiber length.

The output transmission spectrum is not varied from the case without the polarizer. This confirms the prediction from the theoretical study.

The experimental results for both structures at different fiber lengths are shown in Fig. 3. The transmission spectrum from either one of the cores shows almost periodic transmission. This reflects the fact that for different wavelengths an identical fiber length leads to a different phase difference between the two supermodes. The smaller air-filling fractions and much closer core-to-core separation ($[d/\Lambda]_A=0.35$, $S_A=\sqrt{3}\Lambda$ and $[d/\Lambda]_B=0.56$, $S_B=3\Lambda$) has resulted in a much shorter beat length for structure A than for structure B.

The wavelength spacing of two nearest transmission minima, $\Delta\lambda$, depends on the wavelength, indicating the dependence of the beat length on wavelength, as suggested by Eq. (4). From the measurements it is determined that by cutting back the twin-core mPOF A from 0.55 to 0.5 m and then to 0.363 m, the periodic wavelength spacing is increased from 4.7 to 5.0 nm and then to 8.1 nm (near 940-nm wavelength). This periodicity should be inversely proportional to the length of the fiber, according to Eq. (4). This is confirmed by plotting the measured $\Delta\lambda/\lambda$ of structure A versus fiber length L as shown by the fitted solid line in Fig. 4, which shows an inverse proportionality with a chi-squared value $R=0.9968$. From the transmissions in Fig. 3, we determine the measured beat lengths at different wavelengths according to Eqs. (2) and (4). The experimental data points are plotted in Fig. 5(a). When an automatic power-function fit in the form of Eq. (2) is used, the wavelength dependence of the beat length is found to be $L_c=0.00384\lambda^{-1.276}$ for fiber A. The value $\eta=1.276$ is reasonably close to the calculated values $\eta^x=1.143$ and $\eta^y=1.184$, but the uncertainty in η is quite large (44.3%), due to the large scatter in the experimental data. To show this, we also perform a curve fit to these data with the calculated value of the coefficient η from Sec. 2. We use $\eta=1.143$ and fit Eq. (2) again with C as the fitting parameter, and a new power function $L_c=0.00393\lambda^{-1.143}$ with an acceptable chi-squared value ($R=0.9177$) is obtained as shown in Fig. 5(a). The uncertainty in η would be mitigated by increasing the wavelength range over which the beat lengths were measured, but that recourse is limited by the usable transmission window of the polymer fiber (from 500 to 900 nm). The deviation between the simulation results ($C=0.01$) and the experimental data ($C=0.00393$) is attributed to the extreme dependence of the beat length on the air-filling fraction and the structure asymmetry.[9] At the same time, an approximation is utilized to average the parameter λ, which is a drawback of our measurement as compared with elasto-optic probe methods.[12]

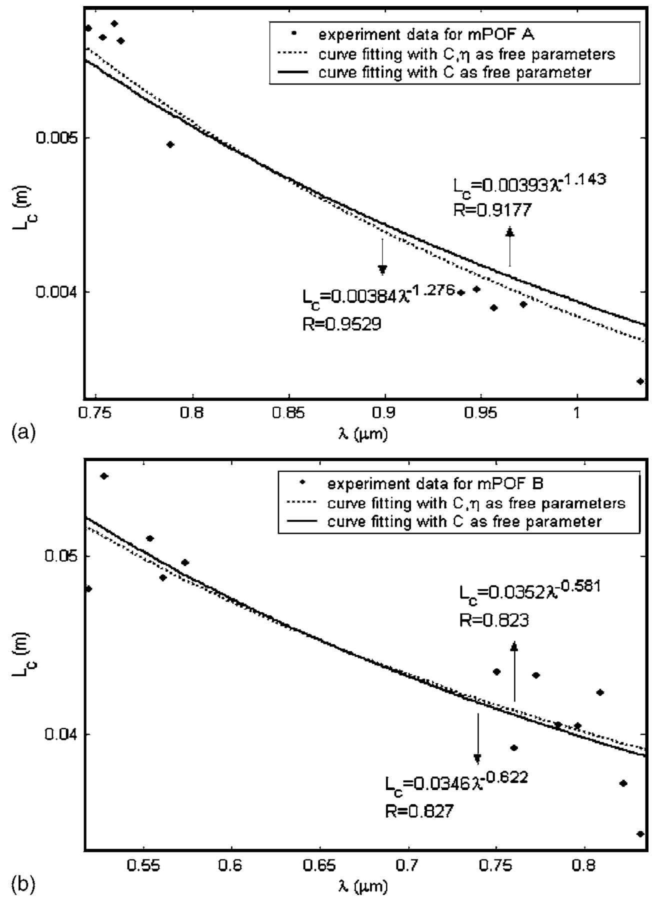


Fig. 5 Measurements of the beat length for (a) mPOF A and (b) mPOF B. The dashed curves are the fitting results with C and η as free fitting parameters, and the solid curves with only C as the fitting parameter.

When cutting the twin-core mPOF structure B from 0.895 to 0.685 m and then to 0.51 m, the inverse proportional trend of wavelength spacing is not as obvious. The chi-squared value of the dotted fitting curve in Fig. 4 is 0.7193. We believe the reason for this is that for fiber B, the beat length is just under 10% of the fiber length (as opposed to about 1% for fiber A), and as a result, the fringes in the transmission spectrum have quite large spacing. This results in a discrepancy from the prediction of Eq. (4), which relies on the assumption $\Delta\lambda/\lambda \ll 1$.

The measured beat length variation with wavelength is shown by the points in Fig. 5(b). When an automatic power function fit of the form of Eq. (2) is used, the wavelength dependence of the beat length is found to be $L_c = 0.0352\lambda^{-0.581}$ for this fiber. This is in reasonable agreement with the calculated result, $\eta^x = 0.622$ and $\eta^y = 0.628$, for the wavelength dependence of the beat length of fiber B, though again the uncertainty is large (65.3%) due to scatter. Therefore we again fix the calculated value of η and find $L_c = 0.0346\lambda^{-0.622}$ with $R = 0.827$. As expected, the coefficient C is much larger than was found for structure A ($C = 0.00393$), because the coupling is much weaker. On comparing the measured results of structures A and B, a similar trend of the trade-off between coupling coefficient and coupling-coefficient dispersion is observed to that in the numerical simulations.

4 Conclusion

We have observed and studied the light coupling effects in twin-core mPOFs. Both theoretical modeling and experimental measurements are reported for two different structures. The wavelength dependence of the intercore beat length is directly obtained from the spectrum. Within the experimental error, the measurement results show reasonably good agreement with the numerical simulations, especially when the structure has a short beat length.

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References

1. P. V. Kaiser and H. W. Astle, "Low-loss single-material fibers made from pure fused silica," *Bell Syst. Tech. J.* **53**, 1021–1039 (1974).
2. T. A. Birks, P. J. Roberts, P. St. J. Russell, D. M. Atkin, and T. J. Shepherd, "Full 2-D photonic bandgaps in silica/air structures," *Electron. Lett.* **31**, 1941–1942 (1995).
3. Y. Zhu, P. Shum, H. Bay, M. Yan, X. Yu, J. Hu, J. Hao, and C. Lu, "Strain-insensitive and high-temperature long-period gratings inscribed in photonic crystal fiber," *Opt. Lett.* **30**, 367–369 (2005).
4. B. J. Eggleton, P. S. Westbrook, C. A. White, C. Kerbage, R. S. Windeler, and G. L. Burdge, "Cladding-mode resonances in air-silica microstructure optical fibers," *J. Lightwave Technol.* **18**, 1084–1100 (2000).
5. H. Kim, J. Kim, U. Paek, B. H. Lee, and K. T. Kim, "Tunable photonic crystal fiber coupler based on side-polishing technique," *Opt. Lett.* **29**, 1194–1196 (2004).
6. P. M. Blanchard, J. G. Burnett, G. R. G. Erry, A. H. Greenaway, P. Harrison, B. Mangan, J. C. Knight, P. St. J. Russell, M. J. Gander, R. McBride, and J. D. C. Jones, "Two-dimensional bend sensing with single, multi-core optical fibre," *Smart Mater. Struct.* **9**, 132–140 (2000).
7. K. Saitoh, Y. Sato, and M. Koshiba, "Coupling characteristics of dual-core photonic crystal fiber couplers," *Opt. Express* **11**, 3188–3195 (2003).
8. B. J. Mangan, J. C. Knight, T. A. Birks, and P. St. J. Russell, "Dual-core photonic crystal fibre," in *Summaries of Papers Presented at the Conf. on Lasers and Electro-Optics*, IEEE (1999), pp. 559–560.
9. W. E. P. Padden, M. A. van Eijkelenborg, A. Argyros, and N. A. Issa, "Coupling in a twin-core microstructured polymer optical fiber," *Appl. Phys. Lett.* **84**, 1689–1691 (2004).
10. G. Barton, M. A. van Eijkelenborg, G. Henry, M. C. J. Large, and J. Zagari, "Fabrication of microstructured polymer optical fibres," *Opt. Fiber Technol.* **10**, 325–335 (2004).
11. J. D. Joannopoulos, R. D. Meade, and J. N. Winn, *Photonic Crystals*, Princeton Univ. Press, Princeton, NJ (1995).
12. G. D. Peng, T. Tjugiarto, and P. L. Chu, "Accurate elasto-optic probe method for measurement of coupling length in twin-core optical fiber," *Appl. Opt.* **33**, 1004–1010 (1994).

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