APPLIED PHYSICS LETTERS VOLUME 84, NUMBER 10 8 MARCH 2004

Coupling in a twin-core microstructured polymer optical fiber

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(Received 1 August 2003; accepted 6 January 2004)

Theoretical calculations and experimental results are reported for a microstructured polymer optical fiber twin-core coupler. Beat lengths are calculated using a fully vectorial, Fourier decomposition method, which show that the beat length is extremely sensitive to any core asymmetry. Reasonably good agreement between theory and experiment is obtained. *© 2004 American Institute of Physics.* [DOI: 10.1063/1.1651651]

Over the last 6 years, interest in photonic crystal fibers (PCFs) has increased dramatically. A PCF consists of a series of microscopic air holes running parallel to the fiber axis. The microstructure usually consists of a periodic arrangement of holes surrounding a defect that acts as the core which can guide light.[1] The defect can be formed in a number of ways, such as the absence of one or more air holes, or by creating an air hole of a different size. In the former case this leads to a high-index core relative to the cladding, and such fibers can guide by a modified form of total-internal reflection. The latter case can yield a low-index core relative to the cladding and these fibers can guide by the photonic band gap effect.[2]

In PCFs, one can easily adjust parameters such as the hole diameter and spacing, and large index contrasts can be obtained. Therefore, PCFs can be designed to display a diverse range of behaviors compared to conventional fibers, offering strong potential for a wide variety of photonic devices. For example, they can be made endlessly single-mode,[3] have either very large or small nonlinearity,[4] and have unusual dispersion characteristics such as ultraflat dispersion.[5] Also, multicore bend sensors,[6] twin-core strain sensors,[7] and fiber couplers[8] have been studied.

Here we report on the realization of a microstructured polymer optical fiber (MPOF) twin-core coupler. Unlike silica PCFs, which are generally fabricated by stacking an array of silica capillaries and rods, MPOF preforms can be made by a variety of techniques, for example by simply drilling the desired pattern of holes and then drawing the preform.[9] This allows for potentially more complex designs. The twin-core MPOF reported here was fabricated by omitting two air holes from an otherwise periodic triangular lattice. A single air hole was left between the two cores. The fiber was drawn from a poly(methylmethacrylate) (PMMA) structured preform of 80 mm diameter to a diameter of 200 μm in two stages.[9] An optical microscope image of the microstructure is shown in Fig. 1. The fiber has a hole spacing or pitch $\Lambda = 4.08$ μm and a hole diameter $d = 2.37$ μm.

Using the earlier parameters, the structure was modeled theoretically using a recently developed Fourier decomposition method.[10] The method is fully vectorial and calculates the confinement loss of the modes, taking into account the material dispersion of the substrate (PMMA). As shown in Fig. 1, one of the holes bounding the core is significantly larger than the other holes. It is well known that twin-core devices are very sensitive to perturbations to the core and thus it was decided to model the structure with and without the hole asymmetry to highlight its effect. All other holes in the fiber were assumed to be of identical size. The structure that was numerically modeled is shown in Fig. 2. It can be seen that it has less rings of holes surrounding the core than the real structure. This was done so as to speed up the numerical simulations. More rings of holes would have required more Fourier components. The main effect of this simplification is to overestimate the confinement loss of the structure, which has little effect on the real part of the effective index of the modes and, hence, will have a negligible effect on the beat length, which is the property of interest.

Initially the perfectly symmetric structure was modelled. First, a scalar calculation was performed using 600 radial steps and 80 azimuthal Fourier components (as required to

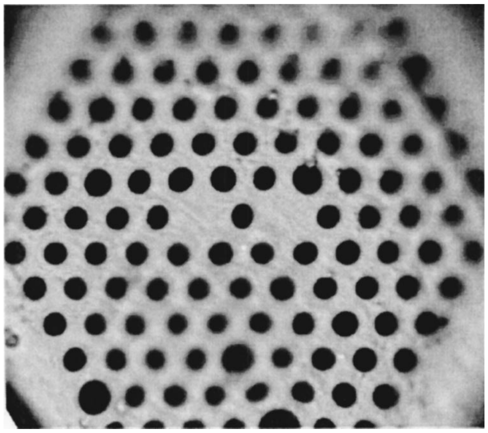

FIG. 1. Optical micrograph of the twin-core microstructured polymer optical fiber with an average hole spacing $\Lambda = 4.08$ μm and a hole diameter $d = 2.37$ μm. The outer diameter of the fiber is 200 μm.

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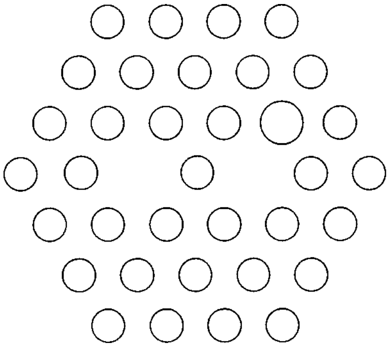

FIG. 2. Diagram of the modeled structure with hole spacing $\Lambda = 4.08$ μm and a hole diameter $d = 2.37$ μm, and one 30% larger air hole.

achieve the appropriate accuracy in the value of the effective index), at several wavelengths between 0.4 and 0.95 μm. From this, the wavelength dependency of the beat length was determined.[11] In the scalar case there is an even and odd supermode with azimuthal symmetry of $m=0$ and $m=1$. The beat length which is given by $L_B = \lambda/\Delta n$, where Δn is the difference between the mode refractive indices, was found by a nonlinear least-squares analysis, to obey a relationship of the form $L_B \propto \lambda^{-1.68}$ $(R^2 = 0.9987)$. At 0.675 μm, L_B has a value of 0.40 m.

For the vector calculation the mode structure is more complex as each mode from the scalar case is split: there are now two $m=0$ modes and two $m=1$ modes. The intramode splitting is of the same order of magnitude as the intermode splitting. As expected the modes of the same symmetry class are orthogonally polarized, with the $m=0$ modes being odd and the $m=1$ modes being even. In the absence of perturbations so that orthogonally polarized modes do not couple, there are now two beat lengths. At 0.675 μm these both have values of 0.44 m and $L_B \propto \lambda^{-1.67}$ was found, very similar to the scalar case.

Finally, the asymmetric structure was modeled. It was estimated that one of the holes surrounding the core is approximately 30% larger than the others. Since this structure has no symmetry, there is only one mode class $m=0$ which consists of four modes. There are two orthogonally polarized modes in the symmetric core polarized along the x and y axes. The other two modes are in the asymmetric core: in this case one mode is polarized at approximately 48° to the x axis, while the other is polarized at approximately $-56°$ to the x axis. Note that these two modes are polarized 104° to each other. The modes are still orthogonal in the sense that $\int d^2 r (\mathbf{E} \times \mathbf{H}) \cdot \hat{\mathbf{z}} = 0$, although locally $\mathbf{E} \times \mathbf{H}$ need not be zero in cases of high index contrast. The intramode splitting in this case is two orders of magnitude smaller than the intermode splitting. Also, the splitting between modes in the asymmetric core is approximately three times that in the symmetric core, which shows the large hole has significantly more effect than the other core on the splitting. Strictly there are now four possible beat lengths, however, due to the intermodal splitting being so much larger than the intramodal splitting they are all quite close. For the case of 400 radial steps and 60 azimuthal Fourier components (note that this was the largest number of components that could be used due to memory constraints), L_B is approximately 5.8 mm at $\lambda = 0.675$ μm. The wavelength dependence was found to be $L_B \propto \lambda^{-0.971}$. Clearly the asymmetry has resulted in a dramatic decrease in the beat length and a reduction in the wavelength dependence. To test the sensitivity of the beat length to the size of the perturbing hole, two more calculations were performed with hole sizes 25% and 35% bigger than the others. In these cases L_B was approximately 8.25 and 4.46 mm, respectively, showing that the beat length is highly dependent on the hole size. Furthermore, the dependence of L_B on wavelength was calculated for hole sizes 5%, 10%, 15%, 20%, and 35% larger than the others. It was found that the relationship was nearly independent of hole size with $L_B \propto \lambda^{-0.97 \pm 0.005}$. It is believed that the differences between the power law dependence for the symmetric and asymmetric structures is due to polarization effects. The presence of a perturbing hole dramatically alters the polarization of the mode in the asymmetric core, which in turn affects mode coupling.

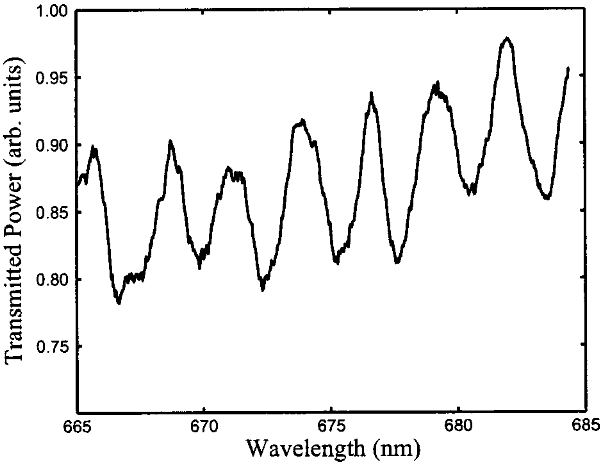

FIG. 3. Spectrum of the light transmitted through one of the cores of the twin core fiber shown in Fig. 1.

The beat length of the twin-core MPOF shown in Fig. 1 was then measured. The single-mode nature of the individual cores in the fiber was tested by launching coherent light from a HeNe laser into both cores by illuminating the end of the fiber uniformly using an objective lens. This produced a clear interference pattern at the output end of the fiber with high fringe visibility. In addition, the mode profiles in the two cores were found to be insensitive to fiber bending and changes in the launching conditions. This confirms that the cores are single mode at a wavelength of 633 nm. (In the numerical modeling, L_B was calculated by considering the splitting in the first two modes only, requiring the cores to individually be single mode.) We should note that although we found each core to be single mode, theory indicates that this should not be true if our measurements are correct. The ratio $d/\Lambda = 0.58$ would indicate that higher order confined modes should exist. That we failed to find evidence of such modes may indicate that the true hole diameter is smaller than measured from the micrographs.

An experimental measurement of L_B was obtained by launching white light into only one core and taking a spectrum of the output of the same core (see Fig. 3). Launching into a single core was achieved using two methods; by blocking one of the cores and illuminating the fibre end uniformly using an objective lens or by butt-coupling just one core to a standard single-mode silica fiber. The spectrum showed almost equally spaced transmission minima (wavelengths for which the light had coupled to the other core), with a spacing that increased slightly with wavelength. The moderate modulation depth as observed in the measured spectrum, reflects that only a small fraction of the power is coupled back and forth between the cores. This is a result of the asymmetry in the fiber structure. From the spectrum we find that only 10% of the power is coupled between the cores (as opposed to 100% for a symmetric structure).

Using the wavelength dependence of L_B obtained from the numerical modeling, and the method reported earlier,[12] we obtain values of 3.6 and 2.4 mm for L_B at $\lambda = 0.675$ and 0.940 μm, respectively. The theoretically calculated values, using the fully vectorial case with one 30% larger air hole, are 6.3 and 4.6 mm at these wavelengths. Differences between the theoretical and experimental values are attributed to the very high sensitivity of L_B to the size of the holes in the fiber and the problem that optical microscopy can lead to errors in the estimation of hole sizes.[13] In addition, only the size difference of the largest hole was taken into account in the calculations—the irregularities in the sizes and shapes of the other holes (5%–10%) were not accounted for. To obtain further quantitative agreement the complete fiber structure would have to be modeled, with accurate sizes, positions, and shapes of each of the holes, which is beyond the scope of the current report.

We reported on theoretical and experimental results obtained for a twin-core microstructured polymer optical fiber. Given the slight imperfections in the fiber and the strong sensitivity of the coupling length on the fiber parameters and symmetry, the calculated and measured coupling lengths were found to be in reasonable agreement.

The authors would like to thank Dr. Leon Poladian for many helpful discussions throughout this work, the Australian Partnership for Advanced Computing (APAC), and Sydney Vislab for access to supercomputer facilities. This work was partly supported by the Australian Photonics CRC, the Australian Research Council (ARC), and Redfern Photonics Pty. Ltd.

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