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Photonic-Molecule Modes of a Microstructure Cobweb Fiber

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Abstract—A microstructure fiber with a core in the form of a cyclic polyatomic photonic molecule is created. Air holes arranged in a two-dimensionally quasi-periodic structure in the cladding of this fiber and a larger hole at the center of the fiber form a cyclic-molecule-like structure, consisting of an array of small-diameter glass channels linked by narrow bridges, around the central hole. This photonic-molecule microstructure-integrated bundle of fibers can guide the light through total internal reflection, providing a high light confinement degree due to the large refractive index step. The analogy between guided modes of the light field in such a fiber and electron wave functions in a cyclic polyatomic molecule is shown to provide a deeper insight into the properties of waveguide modes of the created fiber.

Within the past few years, the development of microstructure (MS) fibers [1–6] has resulted in an impressive progress in various areas of optical science, permitting single-mode waveguiding to be realized within a very broad spectral range [2], allowing supercontinuum to be generated starting with subnanojoule energies of femtosecond pulses [7], and leading to revolutionary changes in optical metrology [8–10]. Various designs of MS fibers have been proposed during this period, promoting extensive applications of these fibers in various fields of applied optics and fundamental science. It was shown, in particular, that MS fibers with a photonic-crystal cladding [1–4] may provide new regimes of waveguiding due to a high reflectivity of the cladding around the photonic band gap [4] and allow many of the ideas discussed in connection with photonic crystals [11, 12] to be realized. The possibility to design MS fibers with different configurations of the core and the cladding helps to tailor the dispersion of such fibers [2, 6, 13, 14], making these fibers very useful for nonlinear optics and short-pulse generation and control. The degree of light confinement in the fiber core and, hence, the degree to which nonlinear optical processes are enhanced also depend on the design of the fiber [15, 16], with the air-filling fraction of the fiber determining the effective refractive index of the cladding. With a special design of the core and the cladding, an MS fiber can be made highly birefringent [17], as it was demonstrated, for example, for a cobweb photonic-crystal fiber [18]. These examples illustrate the importance of design aspects for various functions of MS fibers, motivating further search for new approaches in MS-fiber patterning.

In this paper, we will examine optical properties of MS fibers having a core with the cross section in the form of a cyclic photonic molecule (Figs. 1a, 1b). Air holes arranged in a two-dimensionally quasi-periodic structure in the cladding of this fiber and a larger hole at the center of the fiber form a cyclic-molecule-like structure, consisting of an array of small-diameter glass channels linked by narrow bridges, around the central hole (Fig. 1a). This photonic-molecule (PM) microstructure-integrated bundle of fibers can guide the light through total internal reflection, providing a very high light confinement degree due to the large refractive index step. We will show that dispersion properties of guided modes change as we switch between different photonic-molecule modes by varying the light field distribution at the input end of such an MS fiber.

Microstructure fibers were fabricated with the use of the technique that now becomes standard [1, 19] and that involves stacking capillaries into a preform and then pulling this preform at elevated temperatures. A preform with a capillary of a larger inner diameter at the center was used to fabricate MS fibers studied in this paper, resulting in a special configuration of holes shown in Fig. 1a. This is essentially a hollow-core photonic-crystal fiber design, demonstrated earlier by Cregan *et al.* [4], but with a very thin wall separating the central hole from the rest of the structure and with a very high refractive index step between this wall and the adjacent areas, which is achieved due to the high air-filling fraction of the microstructure (Fig. 1a).

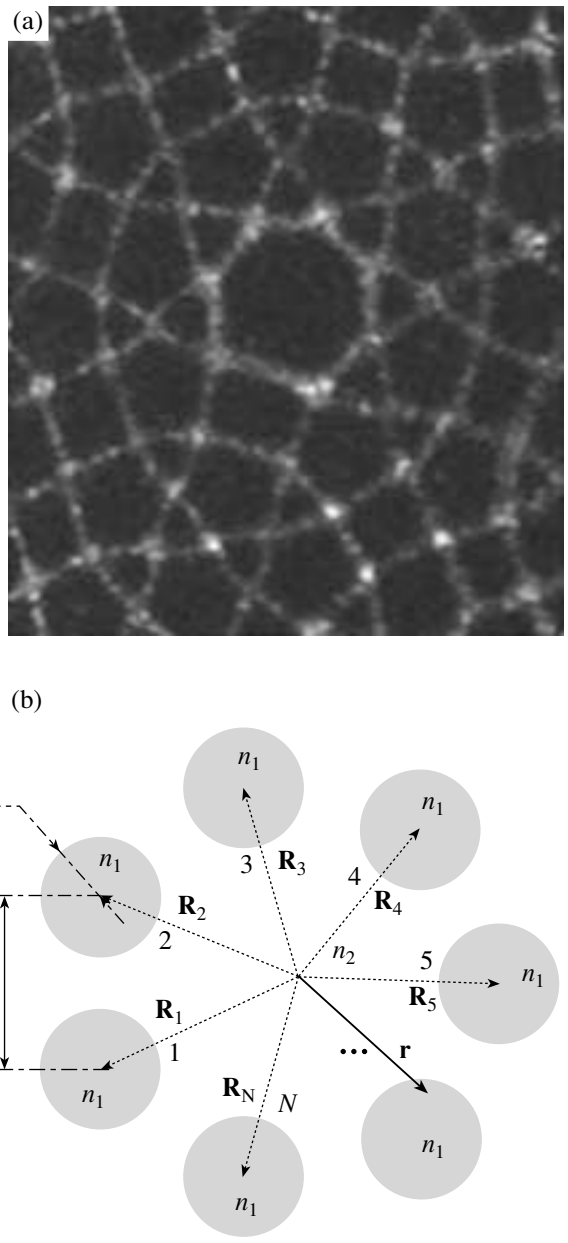

Fig. 1. (a) A cross-sectional image of a photonic-molecule microstructure-integrated bundle of fibers with a radius of each fiber in the bundle equal to 2 μm and the distance between the neighboring fibers of 7.4 μm. (b) A photonic-molecule model for an optical fiber where the light is guided along a set of N cores with the refractive index n_1 surrounded by a material with the refractive index n_2 and linked by narrow bridges with the distance between the neighboring cores equal to R.

Instead of air-guided modes, considered in a very illuminating way in earlier work [4], we are interested in the light guided along the cladding, forming a narrow ring around the hollow core of this fiber. This cladding, as is readily seen from Fig. 1a, is reminiscent of the configuration of atoms linked by chemical bonds in a cyclic polyatomic molecule consisting of identical atoms (Fig. 1b), which brings us to an idea of using a photonic-molecule analogy to understand optical properties of such a waveguiding structure.

Earlier, an elegant model of a diatomic PM has been used to describe the modes of coupled semiconductor [20] and dye-doped polymer [21] microcavities. Below, we will extend this analogy by introducing a polyatomic photonic molecule. This effort will later prove to be quite rewarding by providing us with an illustrative and physically clear model of dispersion properties and mode structure of the considered optical fiber. The physics behind the analogy between a bundle of coupled MS-integrated fibers and a polyatomic molecule is that the way the distribution of the refractive index in the plane of Fig. 1b, showing the cross section of a bundle of coupled fibers, modulates the light field is similar to the way the distribution of potential in a polyatomic molecule modifies the electron wave function. Mathematically, this analogy stems from the similarity of coupled-mode-theory equations for an array of fibers [22] and perturbation-theory equations for the electron wave function in a polyatomic molecule.

We will restrict ourselves to a scalar-wave-equation approximation in this paper, ignoring at this stage many of potentially useful polarization effects, which will be considered elsewhere [23]. Since the strongest mode coupling is achieved for waveguide modes with equal propagation constants in a photonic-molecule bundle of identical elementary fibers (Fig. 1b), we will neglect also the coupling of modes with different mode indices. The modes of the light field in the PM fiber can be then represented as superpositions of modes of elementary fibers forming our microstructure:

$$\Psi(\mathbf{r}) = \sum_n A_n f(\mathbf{r} - \mathbf{R}_n), \tag{1}$$

where $\mathbf{r}$ is the radius vector in the plane of fiber cross section (the plane of Fig. 1b), $\mathbf{R}_n$ are the coordinates of the nth fiber center (Fig. 1b), and A_n and $f(\mathbf{r} - \mathbf{R}_n)$ are the amplitude and the transverse distribution of the field in the waveguide mode of the nth fiber in the considered microstructure.

Since only the neighboring fibers are coupled to each other in our two-dimensional photonic molecule (Figs. 1a, 1b), the coupled-mode equations for the field amplitudes can be written as [22, 24]

$$\frac{dA_n}{dz} - i\beta A_n - i\alpha(A_{L(n)} + A_{R(n)}) = 0, \tag{2}$$

where β is the propagation constant for the relevant mode of an isolated fiber,

$$\alpha = \frac{\omega^2}{2\beta c^2}\frac{\int \Delta\varepsilon(\mathbf{r}) f(\mathbf{r} - \mathbf{R}_{n'}) f^*(\mathbf{r} - \mathbf{R}_n) d\mathbf{r}}{\int |f(\mathbf{r} - \mathbf{R}_n)|^2 d\mathbf{r}}$$

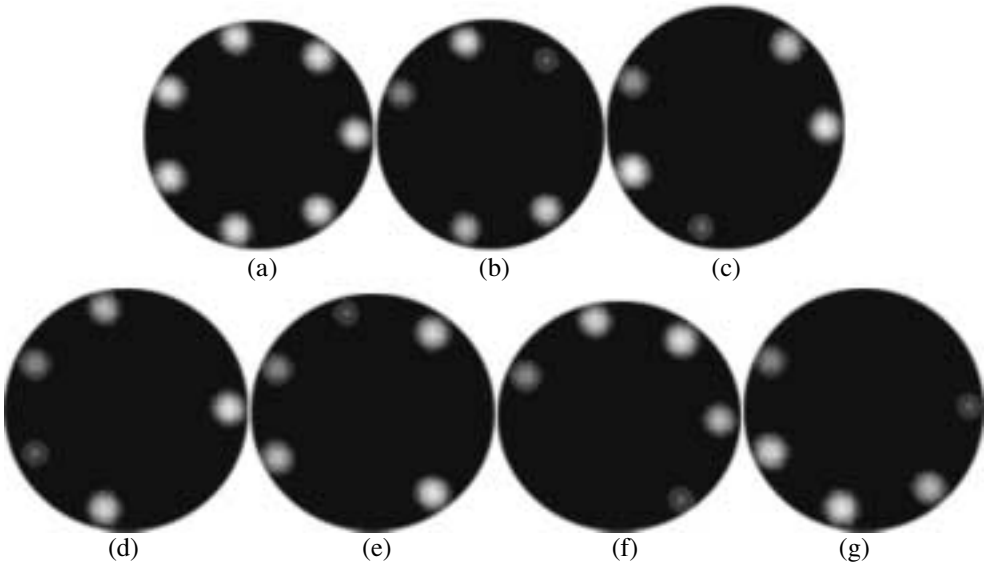

Fig. 2. Light intensity distributions in (a) PM_1, (b) PM_2, (c) PM_3, (d) PM_4, (e) PM_5, (f) PM_6, and (g) PM_7 modes of a seven-core photonic-molecule fiber. The radius of a single elementary fiber in the photonic-molecule fiber structure is 2 μm, the distance between the neighboring fibers in the photonic-molecule structure is 7.4 μm.

(ω is the radiation frequency, $\Delta\varepsilon(\mathbf{r})$ is the deviation from the unperturbed dielectric constant n_2^2 at a given point with a radius vector $\mathbf{r}$) is the coefficient characterizing mode coupling in nth and n'th fibers, and

$$L(n) = \begin{cases} n-1, & n>0 \\ N, & n=0, \end{cases}$$

$$R(n) = \begin{cases} n+1, & n<N \\ 1, & n=N. \end{cases}$$

The propagation constants can now be found from the characteristic equation corresponding to the set of equations (2). In the general case of arbitrary N, these propagation constants can be calculated with the use of numerical methods. There are several simple analytical solutions, however, that provide useful physical insights into the dispersion of the PM fiber. In particular, a symmetric field distribution,

$$\Psi_1(\mathbf{r}) = A\sum_n f(\mathbf{r}-\mathbf{R}_n), \qquad (3)$$

where A is a constant, is allowed by Eq. (2) for any N. This symmetric mode of our fiber (Fig. 2a) is similar to a symmetric wave function of a polyatomic molecule. The propagation constant for such a symmetric mode is given by

$$B_1 = \beta + 2\alpha, \qquad (4)$$

which shows that mode coupling in the considered array of fibers results in a renormalization of propagation constants, leading to the increase in the propagation constants in the case of the totally symmetric mode of a PM fiber (curve *3* in Fig. 3).

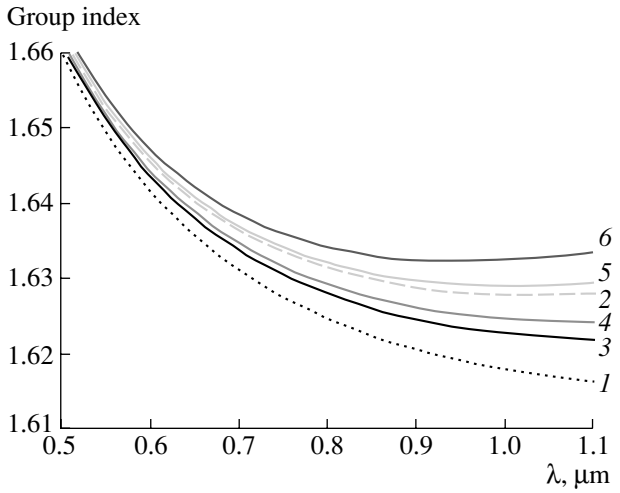

Fig. 3. The group index as a function of radiation wavelength for (*1*) the material of the fiber; (*2*) a single isolated fiber from the considered photonic-molecule structure (or an array of identical fibers completely isolated from one another); and (*3*) PM_1, (*4*) PM_2 and PM_3, (*5*) PM_4 and PM_5, and (*6*) PM_6 and PM_7 modes of a seven-core photonic-molecule fiber ($N = 7$). The radius of a single elementary fiber in the photonic-molecule fiber structure is 2 μm, the distance between the neighboring fibers in the photonic-molecule structure is 7.4 μm.

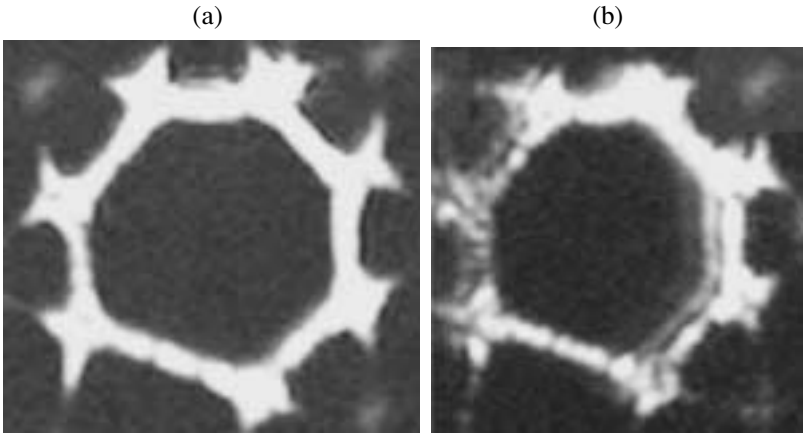

Fig. 4. Images of (a) PM_1 and (b) PM_6/PM_7 modes of a seven-core photonic-molecule fiber excited with 632-nm He–Ne-laser radiation.

An antisymmetric solution

$$\Psi_N(\mathbf{r}) = A\sum_n (-1)^n f(\mathbf{r} - \mathbf{R}_n) \quad (5)$$

is also allowed by Eq. (2) for even N. This antisymmetric mode also has an obvious analogy in quantum chemistry. The propagation constant is then renormalized in accordance with

$$B_N = \beta - 2\alpha. \quad (6)$$

By analogy with the classification of modes in a standard fiber, we identify the fundamental mode of our photonic-molecule fiber as the mode with the largest propagation constant. The highest value of the propagation constant in the case of our PM fiber is achieved for the symmetric mode (see Fig. 2a and curve *3* in Fig. 3). This mode will be, therefore, referred to as the fundamental mode. We introduce the mode index l to enumerate PM-fiber modes, which will be denoted as PM_l modes, starting with $l = 1$, which corresponds to the fundamental PM mode.

We performed calculations for a PM fiber structure that modeled the created MS fiber (Fig. 1a) and that consisted of seven identical elementary glass fibers with a radius $a = 2$ μm. The frequency dependence of the refractive index n_1 for these elementary fibers was approximated with a standard Sellmeier-type equation involving numerical coefficients taken from [25]. The refractive index n_2 of the outer cladding was set equal to the refractive index of atmospheric-pressure air, since the air-filling fraction of the structure was very high (see Fig. 1a). The distance R between the neighboring cores was estimated as 7.4 μm. To estimate the coupling coefficient appearing in Eq. (2), we employed the expression for the coupling coefficient $\alpha = C\lambda$, where λ is the wavelength, from the model of two coupled identical planar waveguides [24]. For characteristic geometric sizes of our structure, this model allows the parameter C to be estimated as 0.016 μm^{-2}. Only lowest order modes of isolated elementary fibers were included in our calculations. The inclusion of higher order modes will, of course, change dispersion branches of a PM fiber and make the analysis much more complicated. The model that includes only fundamental modes of each elementary fiber, on the other hand, allows the general physical features of dispersion of a PM fiber to be understood without reproducing the fiber dispersion in all the details.

Light intensity distributions calculated for the PM_1–PM_7 modes of the created MS fiber are presented in Figs. 2a–2g. The lowest values of the group index, as can be seen from the results of calculations presented in Fig. 3, are achieved for PM fiber modes with smooth profiles. The propagation constant and the group velocity of PM fiber modes decrease with the growth in the number of extrema in the spatial profile of the PM fiber mode. Obviously, the number of elementary fibers in a PM fiber defines the upper bound for the number of such extrema in the profile of the PM fiber mode.

We experimentally studied different PM_l modes in a PM fiber. To excite these modes, we coupled 632-nm radiation of a He–Ne laser into a PM fiber with the use of a 40× microobjective with a numerical aperture of 0.65. Varying the position of the focus of radiation transmitted through this microobjective with respect to the input end of the fiber, we were able to excite all the above-specified PM fiber modes. Radiation coming out of the fiber was collimated with a 20× microobjective with a numerical aperture of 0.65. This radiation transmitted through the fiber was then used to image the output end of the PM fiber onto a CCD array. Figure 4 shows the images of the symmetric (PM_1, Fig. 4a) and asymmetric (PM_6/PM_7, Fig. 4b) modes of the created MS fiber. The images presented in Fig. 4 demonstrate a high localization of light field in PM fiber modes. The results of our measurements also suggest the possibility of changing the dispersion properties of radiation

guided in the created MS fiber by switching between different PM modes, which can be excited with an appropriate field distribution at the input end of the fiber.

Thus, we designed a microstructure fiber with a core in the form of a cyclic polyatomic photonic molecule. Our analysis of dispersion properties and the mode structure of this fiber, performed in terms of the photonic-molecule analogy, shows that the created PM fibers not only represent an interesting object for studying fundamental aspects of photon-localization modes in micro- and nanostructured matter and developing heuristic analogies with quantum chemistry, but also offer several new practical ways of dispersion engineering. Photonic-molecule fibers offer several important options, which seem to advantageously supplement vast opportunities provided by photonic-crystal fibers. In particular, additional dispersion tunability can be achieved in the case of PM fibers by varying the initial conditions at the input end of the fiber, resulting in the excitation of different PM fiber modes. A promising direction for further studies would be to explore the possibility of coherent control of nonlinear-optical cross-action processes in coupled fibers of a PM waveguiding structure by using pulses with different temporal and spatial profiles, frequencies, and initial chirps. It would be of interest also to search for new ways to phase-match nonlinear-optical interactions in such fibers, as well as to examine the potential of PM fibers for pulse compression through self- and cross-phase modulation and supercontinuum generation. The geometry of PM fibers is also advantageous for a broadband evanescent-field spectroscopy of gases or liquids using supercontinuum generation, as well as for the laser guiding of atoms.

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