Novel multi-core fibers for mode division multiplexing: proposal and design principle

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Abstract: We propose a new type of optical fiber called homogeneous multi-core fiber (MCF) to drastically increase the transmission capacity of single fiber using the mode-division multiplexing. In this MCF, identical cores are closely arranged so that the cores are strongly coupled to each other to form coupled modes, each of which corresponds to a transmission channel. A novel mode multi/demultiplexer is proposed to discriminate each coupled mode. To rearrange cores to match the mode multi/demultiplexer, a hybrid configuration of coupled homogeneous with uncoupled heterogeneous multi-core is proposed. An example of hybrid configuration is designed so that the cross-talk becomes sufficiently small.

Keywords: multi-core fiber, coupled mode, mode division multiplexing

Classification: Optical fiber

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1 Introduction

Owing to the demand of traffic capacity increase of optical fiber network, a breakthrough in the transmission capacity per fiber is needed in the near future. It is expected that 100-Gbit/s Ethernet will be commonplace in 2015 and carriers will be able to transport 10 Tbit/s, or more [1]. A breakthrough in the existing design of single-mode fibers is indispensable to achieve large-capacity transmission of over 10 Tbit/s per fiber. One of the promising candidates to expand the capacity is to use a multi-core fiber (MCF). In the past, to increase the cable capacity, several technical programs were managed on multi-core single-mode fibers [2, 3]. In the traditional MCF, the core density is dominated by the core-to-core distance which guarantees a required cross-talk level along a given propagation length resulting from the core coupling.

In this letter, to realize the multi-core fiber solving the coupling problem, we propose a new concept of coupled homogeneous multi-core fiber (homogeneous MCF), which utilizes the coupling between adjacent cores in a positive manner. In the homogeneous MCF, cores with identical index contrast and index profile are closely arranged so that the cores are strongly coupled to each other to form coupled modes. Since each coupled mode corresponds to a transmission channel, the number of transmission channels is equal to that of coupled cores, increasing the packing density. A novel mode multi/demultiplexer is proposed to discriminate each coupled mode at the input/output ends. The design principle is based on coupled waveguide model, and the coupled cores are arranged to match the core arrangement of mode multi/demultiplexer using a planar waveguide.

2 Homogeneous multi-core fiber

The homogeneous MCF proposed here consists of step-index or graded-index single-mode cores with same index contrast and index profile, as shown in Fig. 1 (a), where the core radius a and the relative index difference Δ are all the same–the cladding index is 1.45, and the operating wavelength is 1.55 μm. Now Let us consider a coupled waveguide consisting of four single-mode waveguides as shown in Fig. 1 (b) for simplicity. The modal fields of coupled modes are similar to those of the superposition of fundamental modes in the isolated waveguide cores as shown in Fig. 1 (b), and this difference of modal field and propagation constant can be utilized as the independent transmission channel. However, when the core distance D is the same order of magnitude as the core width, a weak coupling occurs and the difference between propagation constants of coupled modes is small, i.e. the coupled modes are quasi-degenerated. In this case, the mode conversion easily occurs by a small perturbation, such as the small irregularity of core boundary. To prevent the mode conversion, the difference between propagation constants of guided modes should be large. To extend the difference of propagation constant between adjacent coupled modes, a high index contrast and a strong coupling by small core spacing are required as shown in Fig. 1 (c).

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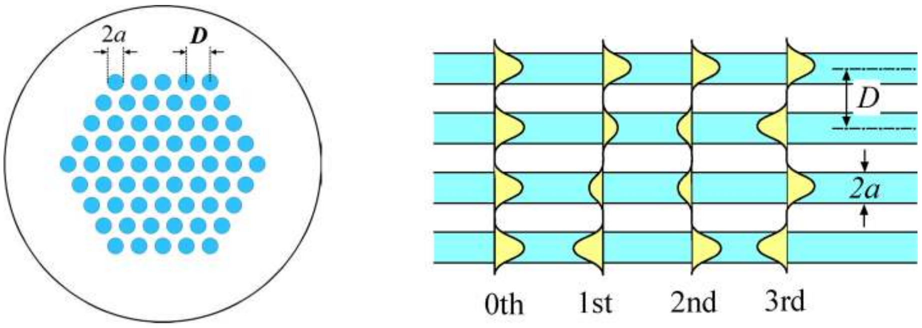
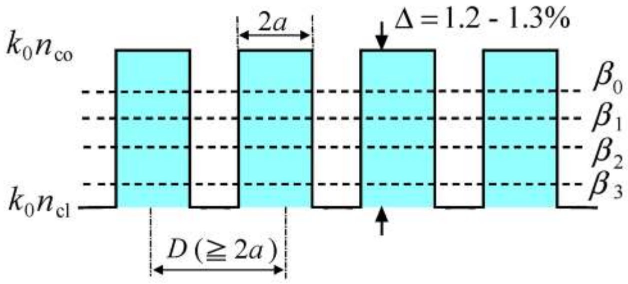


(a) triangular-lattice arrangement (b) simple model of coupled waveguide



(c) desired spacing between propagation constants of coupled modes

Fig. 1. Cross section of homogeneous MCF and simple model of coupled cores.

In order to determine the core pitch necessary for realizing strong couplingbetween any pair of cores, we begin by examining power transfer between two cores 1 and 2 as shown in the inset of Fig. 2 (a), where Δ is the relative refractive-index difference between the core and cladding and is defined as $\Delta = (n_{\rm co}^2 - n_{\rm cl}^2)/(2n_{\rm co}^2)$ with $n_{\rm co}$ and $n_{\rm cl}$ being the core and cladding indices, respectively, and D is the core-to-core distance. The coupling length necessary for complete power transfer between the identical cores ($\Delta_1 = \Delta_2 = \Delta$) is given by $L_c = \pi/(\beta_e - \beta_o)$, where β_e and β_o are the propagation constants of the even and odd modes for the composite structure, respectively. The maximum normalized-power transferred between the non-identical cores (namely, power-conversion efficiency) is given by $F = 1/[1+(\beta_1-\beta_2)^2/(2\kappa)^2]$, where β_1 and β_2 are the propagation constants of the fundamental modes for cores 1 and 2 in isolation, respectively, and κ is the coupling coefficient determined by the spatial overlap of the electromagnetic fields of the fundamental modes for each core in isolation [4]. In order to calculate these propagation constants and electromagnetic fields accurately, we use a full-vector finite-element method which is proven to be the most accurate method for arbitrarily-shaped waveguides with curved boundaries [5]. Since the polarization effect is not extensive, numerical results for the x-polarized (horizontally-polarized in the inset of Fig. 2 (a)) modes are shown by solid lines in Figs. 2 (a) and (b).

Figure 2 (a) shows coupling length $L_{\rm c}$ as a function of core distance D. In this calculation, two identical cores, with core diameter $2a$ of $5\,\mu$m and relative index difference Δ ranging from 1.1% to 1.3%, are separated by

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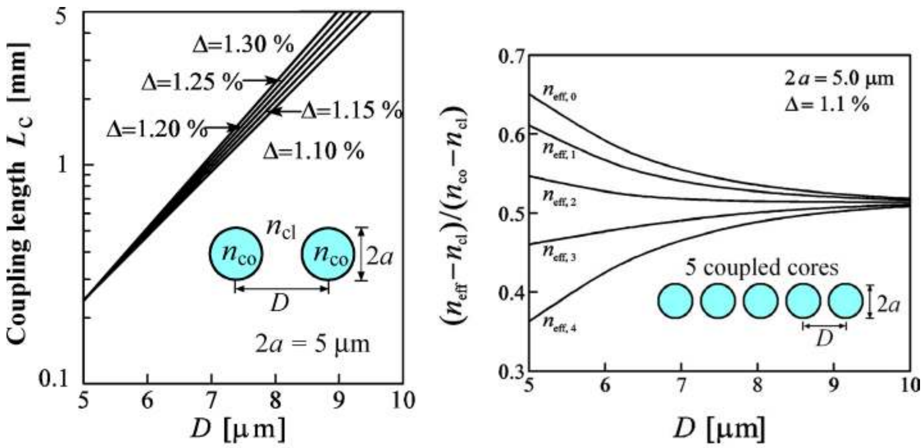

(a) coupling length (b) normalized effective index

Fig. 2. Coupling length and normalized effective index of identical high-Δ cores as a function core-to-core distance.

the core distance D. The single mode condition is $\Delta < 1.304\%$. When the core distance D is equal to the core diameter $2a$, the coupling length is $250\,\mu$m for $\Delta = 1.1\% - 1.3\%$, and the difference of effective indices between even and odd modes is 19% of the index contrast between the core and the cladding. This means that the strong coupling occurs. In the ordinary low-Δ single-mode fiber with $\Delta = 0.3\%$, the difference between effective index n_{eff} $(= \beta/k_0)$ and the cladding index normalized by the index difference $n_{\text{co}} - n_{\text{cl}}$ is about 0.4, and this fraction corresponds to the absolute difference of effective index of 0.0017 assuming the refractive index of core to be 1.45. In the double core coupling case, the absolute difference of effective index is 0.0036, which is much greater than that of single mode fiber. Thus the difference between effective indices of adjacent coupled modes should be the same order of magnitude as that of ordinary single mode fiber.

Figure 2 (b) shows the normalized difference of effective refractive index of each mode $(n_{\text{eff}} - n_{\text{cl}})/(n_{\text{co}} - n_{\text{cl}})$ as a function of core distance assuming five coupled cores with Δ of 1.1%. When the core distance D is equal to the core diameter $2a$, the normalized difference of effective index between lowest and first order modes is about 0.04, which corresponds to the absolute difference of effective index of 0.00064. This value is about 37% of the normalized difference of effective index of ordinary single-mode fiber, and the difference between higher order modes is larger than this value.

3 Mode multi/demultiplexer

To launch the coupled homogeneous MCF discriminating each mode from others, a novel mode multiplexer is required. This can be realized modifying arrayed waveguide grating filter as shown in Fig. 3 (a). This structure is similar to the AWG wavelength multiplexer, except that the slab waveguide at the output region is replaced by the coupled waveguide. Designing that the phase difference between adjacent waveguides in the AWG region

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to be $M\pi/(N-1)$, where N is the number of coupled modes and M is the diffraction order of AWG, the number of input port corresponds to the mode order of coupled mode excited in the coupled waveguide region. Using the low diffraction order of AWG, the wavelength dependence can be reduced. The detailed design will be described in another article in the near future.

4 Hybrid configuration of coupled homogeneous multi-core and uncoupled heterogeneous multi-core fibers

Since the mode multiplexer is realized using the planar waveguide, the coupled core should be arranged in one dimension, instead of triangle-lattice arrangement shown in Fig. 1 (a). A ribbon type fiber, which involves several coupled cores arranged in one dimension, is desirable to satisfy this condition. However, from the view point of the ease of fabrication, the cross sectional shape should be circular. Therefore, the hybrid configuration of coupled and uncoupled groups as shown in Fig. 3 (b) is considered as one of the possible solutions. In the actual fabrication, a preform rod will be prepared by arranging silica rods with triangle-lattice configuration in the same way as the fabrication of holly fibers. Thus the unit equilateral triangle with $5\,\mu$m side should be arranged in the $125\,\mu$m diameter. Each silica rod corresponds to the core with any one of $\Delta = 1.2\%$, 1.25%, 1.3% or the cladding. The distance between the cores with same Δ should be designed to prevent the mutual coupling. It is seen from Fig. 1 (b) of Reference [3] that the core spacing of $39\,\mu$m provides the coupling length L_c of 3000 km for $\Delta = 1.2\%$, and much longer for higher Δ. This coupling length corresponds to the cross talk of -30 dB at 96 km propagation distance. On the other hand, the cross talk between the cores with different Δ is suppressed to be less than -30 dB, because the power conversion efficiency is less than -30 dB when the difference of Δ is 0.05% and the core distance is $13\,\mu$m as shown in Fig. 3 (c), which is the redrawn of Fig. 2 (b) of Reference [3]. According to this design, total of 78 cores can be involved in the $125\,\mu$m core diameter as shown in Fig. 3 (b). In this case, the distance between coupled core groups was designed to be $13\,\mu$m so that the coupled core groups are not coupled to each other.

5 Conclusion

In conclusion, we proposed a new concept of homogeneous MCF. A high index contrast and strong coupling can avoid the mode conversion resulting from small perturbations. Although the periodic power concentration may occur due to the modal interference, this can be avoided by reducing the mutual correlation of light source. To launch the coupled homogeneous MCF discriminating each mode from others, a novel mode multiplexer using AWG is proposed. The core density becomes higher with increasing cladding diameter, for example, $150\,\mu$m, or more. It is important and challenging to develop an efficient technique for optically exciting and detecting signals in a homogeneous MCF.

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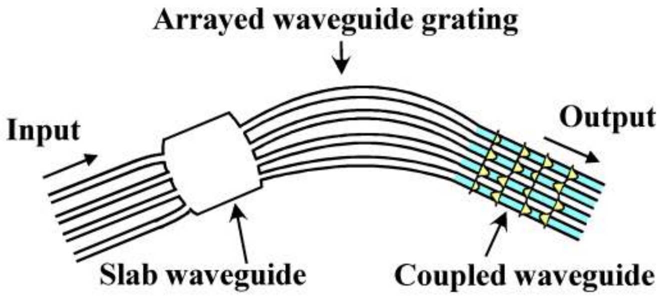
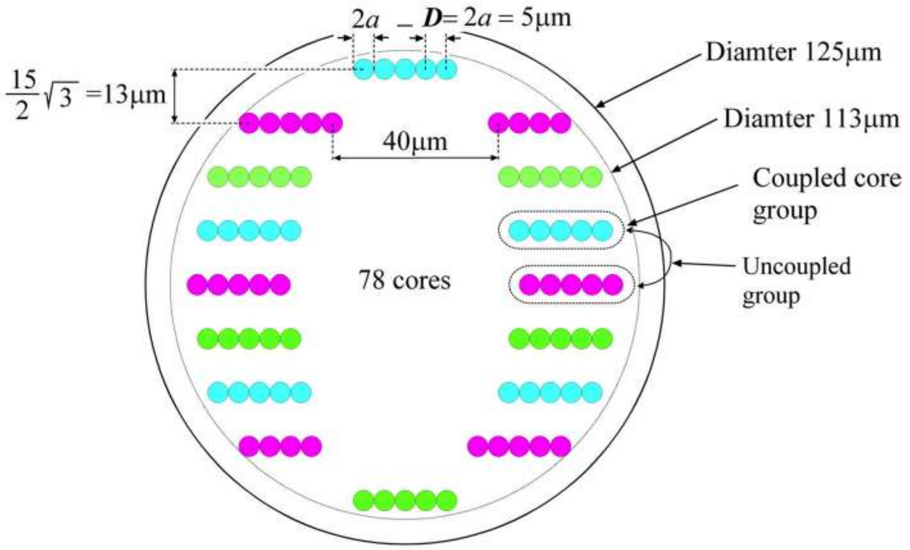
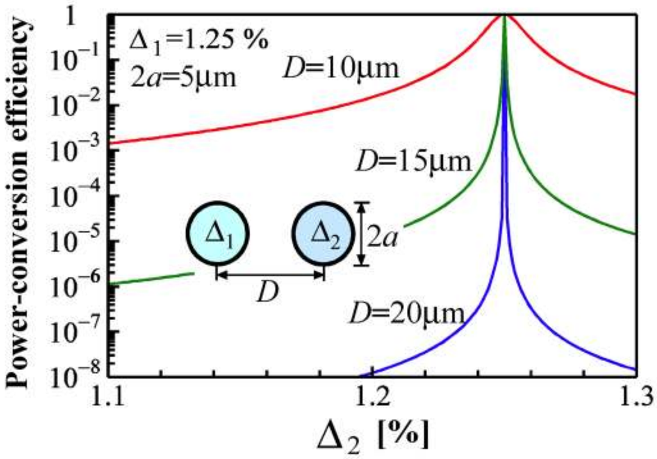


(a) mode multi/demultiplexer using AWG



(b) hybrid configuration of coupled homogeneous multi-core and uncoupled heterogeneous multi-core fibers



(c) power-conversion efficiency of non-identical high-Δ cores as a function of Δ_2 with Δ_1 fixed at 1.25%

Fig. 3. Planar waveguide-type mode multi/demultiplexer and hybrid configuration of homogeneous and heterogeneous MCFs to adapt arrangement of fiber to waveguide-type mode mullti/demultiplexer.

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