ELectronics EXpress

IEICE Electronics Express, Vol.6, No.2, 98–103

Heterogeneous multi-core fibers: proposal and design principle

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Abstract: A new type of optical fiber called heterogeneous multi-core fiber (heterogeneous MCF) is proposed towards future large-capacity optical-transport networks and the design principle is described. In the heterogeneous MCF, not only identical but also non-identical cores, which are single-mode in isolation of each other, are arranged so that cross-talk between any pair of cores becomes sufficiently small. As the maximum power transferred between non-identical cores goes down drastically, cores are more closely packed in definite space, compared to a conventional, homogeneous multi-core fiber (homogeneous MCF) composed of only identical cores.

Keywords: optical fiber, multi-core fiber, non-identical cores

Classification: Optical fiber

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DOI: 10.1587/elex.6.98
Received November 26, 2008
Accepted December 05, 2008
Published January 25, 2009

1 Introduction

Rapid and global spread of the Internet services has been accelerating the

IEICE Electronics Express, Vol.6, No.2, 98–103

need for large-capacity optical-transport networks. Optical-transport networks in 2015 will almost certainly require the capability of transporting higher bit-rate client signals with a much higher total capacity per fiber [1]. It is expected that 100-Gbit/s Ethernet will be commonplace in 2015 and carriers will need to be able to transport 10 Tbit/s, or more [1]. To achieve large-capacity transmission of over 10 Tbit/s per fiber, a breakthrough in the existing design of single-mode fibers might be indispensable. 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 multi-mode fibers [2] and multi-core single-mode fibers [3]. In the traditional, homogeneous MCF all the cores are identical to each other and the core density is dominated by the core-to-core distance which guarantees a required cross-talk level along a given propagation length. It is well-known that when the cores have slight differences in their core indices or radii, the maximum power transferred between the cores goes down drastically [3, 4]. So far, however, this benefit has not been utilized positively to increase the core density.

In this paper, to increase the core density, we propose a new concept of heterogeneous MCF. In the heterogeneous MCF, not only identical but also non-identical cores, which are single-mode in isolation of each other, are arranged so that cross-talk between any pair of cores becomes sufficiently small and cores are more closely packed in definite space, compared to a conventional, homogeneous MCF. To our knowledge, this is the first report on MCF using both identical and non-identical cores aimed at realizing higher core density. The design principle is described and design examples are shown for the heterogeneous MCF with triangular lattice of cores (closest-packed structure) or rectangular lattice of cores. In the rectangular arrangement, although the cores are not the closest packed, it might be easier to splice standard fibers to them than in the triangular one. Specifically, a target value of cross-talk between any pair of cores is chosen to be less than −30 dB along 100 km of propagation.

2 Heterogeneous multi-core fiber

The heterogeneous MCF proposed here consists of several kinds of step-index single-mode cores whose propagation constants are different from each other, where the core radii a are all the same, the core indices n_{co} are different from each other, the cladding index is taken as $n_{cl} = 1.45$, the relative refractive-index difference between the core and cladding is defined as $\Delta = ({n_{co}}^2 - {n_{cl}}^2)/(2{n_{co}}^2)$, and the operating wavelength is assumed to be $1.55\,\mu$m. In order to determine the core pitch necessary for realizing negligible cross-talk between any pair of cores, we begin by examining power transfer between two cores 1 and 2. The coupling length necessary for complete power transfer between the identical cores ($\Delta_1 = \Delta_2 = \Delta$) is given by $L_c = \pi/(\beta_a - \beta_b)$, where β_a and β_b are the propagation constants of the even and odd modes for the composite structure, respectively, and the maxi-

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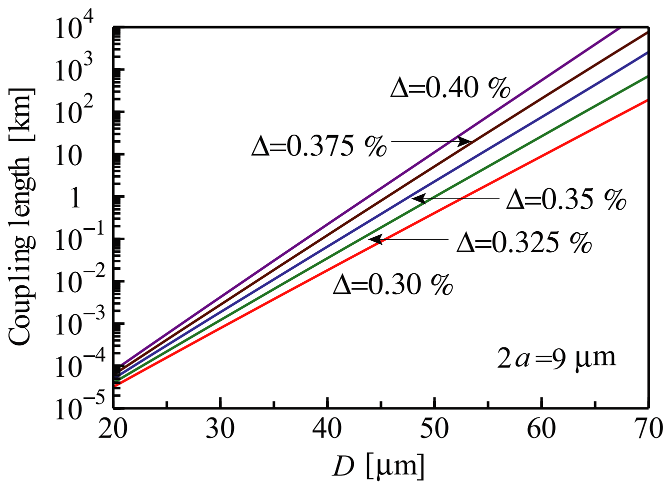
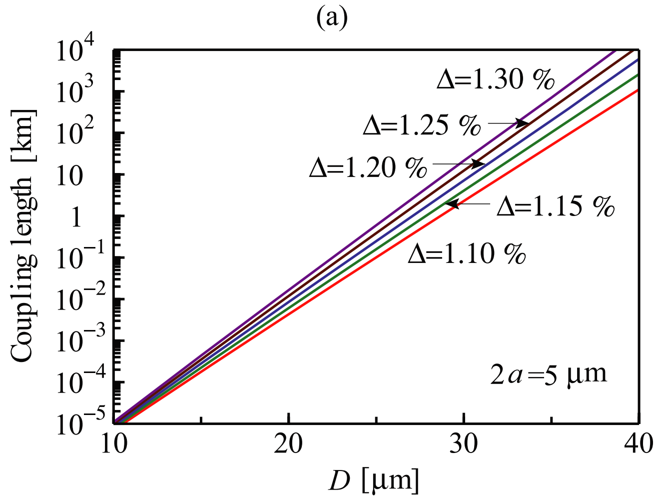
mum normalized-power transferred between the non-identical cores (namely, power-conversion efficiency) is given by $F = 1/[1 + (\beta_1 - \beta_2)^2/(2\kappa)^2]$, where β_1 and β_2 are the propagation constants of the fundamental modes for cores 1 and 2 in isolation, respectively, and κ is the coupling 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].

3 Numerical results

First we consider the heterogeneous MCF with low-Δ cores, as in the usual fiber. Figure 1 (a) shows the coupling length of the identical cores as a function of core-to-core distance D, where the core radius $a = 4.5\,\mu$m and the core with $\Delta < 0.410\%$ is single-mode. Noting that the normalized-power transferred between the identical cores is given by $\sin^2[\pi z/(2L_c)]$ with z being the propagation length, the cross-talk level at the propagation length of 100 km



(a)



(b)

Fig. 1. Coupling length of identical (a) low-Δ and (b) high-Δ cores as a function of core-to-core distance.

DOI: 10.1587/elex.6.98
Received November 26, 2008
Accepted December 05, 2008
Published January 25, 2009

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is less than -30 dB for the coupling length of over 5000 km. It is confirmed from Fig. 1 (a) that the coupling length of 5000 km, or more is achieved for $\Delta > 0.375\%$ and that the core-to-core distance is around 70 μm. Choosing the core-to-core distance between the identical cores in the triangular-lattice pattern to be 70 μm, the pitch Λ between the non-identical cores becomes about 40 μm (70 μm/$\sqrt{3}$) and therefore the maximum normalized-power transferred between the non-identical cores with $\Lambda = 40\,\mu$m should be less than 10^{-3}, corresponding to the target cross-talk level of -30 dB. Figures 2 (a) shows the power-conversion efficiency of the non-identical cores as a function of Δ_2

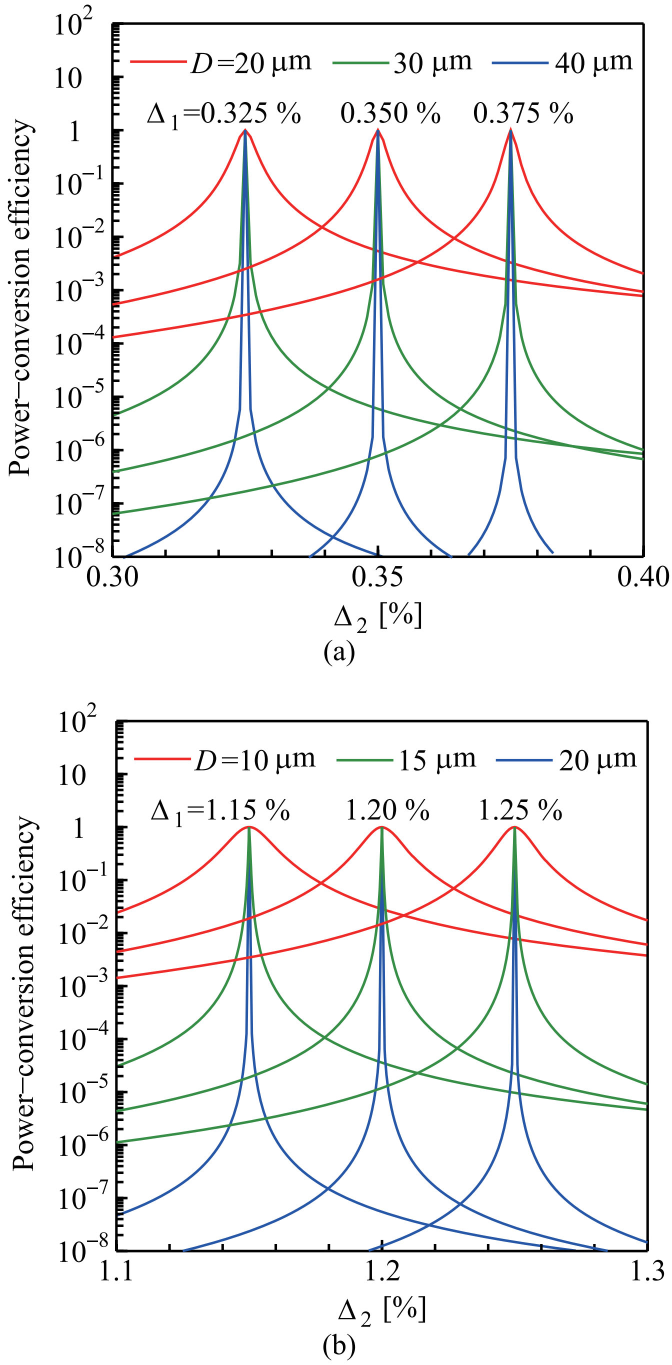

Fig. 2. Power-conversion efficiency of non-identical (a) low-Δ and (b) high-Δ cores as a function of Δ_2.

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with Δ_1 fixed at 0.325%, 0.350%, and 0.375%. Even in the case of $D = 30\,\mu$m ($< 70\,\mu$m$/\sqrt{3}$), as the value of Δ_2 changes slightly from Δ_1 to $\Delta_1 \pm 0.005$%, the power-conversion efficiency is considerably below 10^{-3}. In the case of $D = 40\,\mu$m, the power-conversion efficiency is further reduced to a negligibly small level. Choosing three values of Δ which guarantee a cross-talk level of -30 dB and single-mode operation (for example, $\Delta = 0.38$%, 0.39%, and 0.40%), we can construct a heterogeneous 7-core MCF with cladding diameter of 125 μm, in accordance with the usual standard, as sketched in Fig. 3 (a), where three kinds of single-mode cores are arranged in a triangular-lattice pattern with core pitch of 40 μm and the core-to-core distance of the identical cores is $40 \times \sqrt{3}\,\mu$m $= 69.3\,\mu$m. We can also construct a heterogeneous 6-core MCF as in Fig. 3 (b), where two kinds of single-mode cores are arranged in a rectangular-lattice pattern with core pitches of 35 μm and

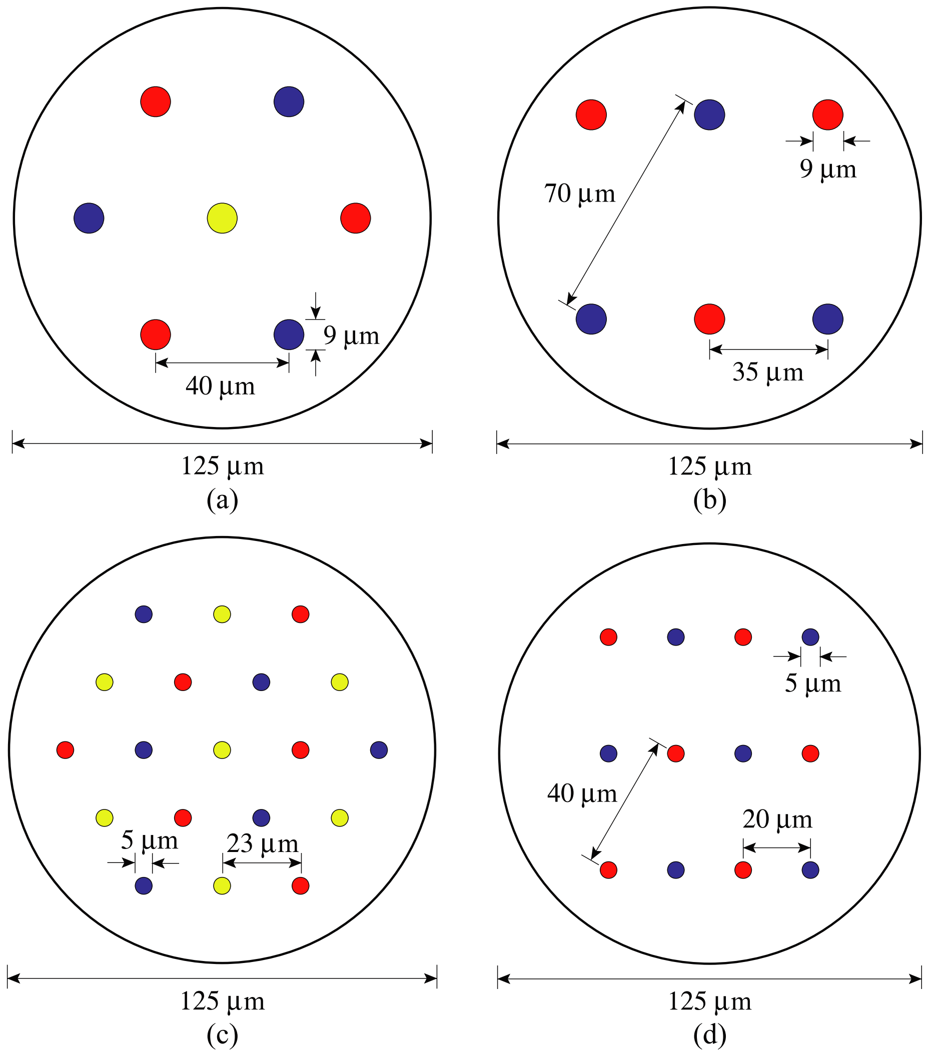

Fig. 3. Heterogeneous low-Δ MCF with (a) 7 cores arranged in triangular-lattice pattern and (b) 6 cores arranged in rectangular-lattice pattern, and high-Δ MCF with (c) 19 cores arranged in triangular-lattice pattern and (d) 12 cores arranged in rectangular-lattice pattern.

DOI: 10.1587/elex.6.98
Received November 26, 2008
Accepted December 05, 2008
Published January 25, 2009

$35 \times \sqrt{3}\,\mu\text{m} = 52.0\,\mu\text{m}$ in the horizontal and vertical directions, respectively, and the core-to-core distance of the identical cores is $70\,\mu\text{m}$.

Next, in order to further increase the core density, we consider the heterogeneous MCF with higher-Δ cores. Figure 1 (b) shows the coupling length of the identical cores as a function of core-to-core distance D, where the core radius $a = 2.5\,\mu\text{m}$ and the core with $\Delta < 1.304\%$ is single-mode. It is confirmed from Fig. 1 (b) that the coupling length of 5000 km, or more is achieved for $\Delta > 1.20\%$ and that the core-to-core distance is around $40\,\mu\text{m}$. Figure 2 (b) shows the power-conversion efficiency of the non-identical cores as a function of Δ_2 with Δ_1 fixed at 1.15%, 1.20%, and 1.25%. As in the case of low-Δ cores, for the slight change of Δ_2 from Δ_1, the power-conversion efficiency goes down drastically. Choosing three values of Δ which guarantee a crosstalk level of -30 dB and single-mode operation, we can construct a heterogeneous 19-core MCF as sketched in Fig. 3 (c), where three kinds of single-mode cores are arranged in a triangular-lattice pattern with core pitch of $23\,\mu\text{m}$ and the core-to-core distance of the identical cores is $23 \times \sqrt{3}\,\mu\text{m} = 39.8\,\mu\text{m}$. We can also construct a heterogeneous 12-core MCF as in Fig. 3 (b), where two kinds of single-mode cores are arranged in a rectangular-lattice pattern with core pitches of $20\,\mu\text{m}$ and $20 \times \sqrt{3}\,\mu\text{m} = 34.6\,\mu\text{m}$ in the horizontal and vertical directions, respectively, and the core-to-core distance of the identical cores is $40\,\mu\text{m}$.

4 Conclusion

We have proposed a new concept of heterogeneous MCF. In the heterogeneous MCF, not only identical but also non-identical step-index single-mode cores are arranged in a triangular- or rectangular-lattice pattern and cores are more closely packed in definite space, compared to a conventional, homogeneous MCF. The core density becomes higher with increasing cladding diameter, for example, $150\,\mu\text{m}$, or more. Graded-index cores could also be introduced in place of step-index cores. Although it is possible to change core radii, a small index change may have a far greater effect than the same fractional change in radius, because the relative refractive-index difference between the core and cladding considered here is very small [4]. It is important and challenging to investigate an efficient technique of optically exciting and detecting the signals in a heterogeneous MCF.

Acknowledgments

The authors would like to thank Prof. Masataka Nakazawa of Tohoku University, Sendai, Japan, Dr. Toshio Morioka of National Institute of Information and Communications Technology, Koganei, Japan, and Prof. Richard M. De La Rue of Glasgow University, Glasgow, United Kingdom for their valuable comments and suggestions.

DOI: 10.1587/elex.6.98
Received November 26, 2008
Accepted December 05, 2008
Published January 25, 2009