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Data interchange across cores of multi-core optical fibers

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ABSTRACT

A novel device for data interchange among space-division multiplexed cores inside MCF is demonstrated using numerical simulations. The device allows complete exchange of all WDM data channels between MCF cores in propagation direction whether the channels have the same or different sets of wavelengths. This is crucial in future MCF optical networks where in-fiber data interchange over space-division multiplexed cores can allow for a simple and fast data swapping among cores without a need for space-division demultiplexing to single-mode single-core fibers. The data core-interchange (DCI) device consists of a graded refractive-index rectangular waveguide enclosing the two interchanged cores in addition to the cladding region in between them. Both finite-difference-time-domain (FDTD) and eigenmode expansion (EME) simulations are performed to verify the device operation and characterize its performance. The simulations demonstrate that the DCI has a very short-length with polarization independent operation, and high performance over the broadband wavelength range S, C, L, and U bands. Moreover, the device shows a high coupling-factor of −0.13 dB with small cross-talk, back-reflection, and return-loss of −26.3, −46.1, and −48.8 dB, respectively.

1. Introduction

Multi-core fiber (MCF) is considered the key solution to increase capacity of future optical networks. The current optical networks capacity is growing exponentially and it is expected to reach the limit despite of using many conventional solutions such as time-division-multiplexing, dense-wavelength-division-multiplexing, p olarization-division-multiplexing, and complex modulation formats [1–5]. The space-division-multiplexing (SDM) in MCF can give another degree of freedom to extend the capacity of future optical networks beyond the current limit. SDM allows each core to carry the same set of wavelengths, and thus it can increase the capacity by 10-times more than conventional one-core single-mode fiber (SMF) networks [6].

The traditional way to perform signal-processing operations on propagating signals along MCF is to convert multicore to single-core SMFs using space-division demultiplexing, and perform required signal-processing operations using conventional SMF devices, then converting back to MCF using SDM. This method is complex, bulky, and expensive to implement. In addition, it can impose a bottle-neck during long transmission distances, which can compromise the MCF advantages. However, the integration of optical signal-processing devices such as couplers, switches, routers, optical cross-connect or add-drop multiplexers within cores and clad of MCF is a very attractive solution that can give a chance to have new and compact in-fiber optical components without compromising the MCF advantages. The proposed data core-interchange (DCI) device here is considered one step toward such in-fiber solutions. The DCI allows for exchange of entire set of WDM data channels between MCF cores in a direct, simple, and cost-effective way that can increase feasibility and efficiency of future MCF optical networks.

In this work, an in-fiber device for data interchange among cores of single-mode homogeneous MCF is proposed. The DCI device can re-direct data from one core to another using a graded-index (GI) clad profile across space between two cores. The DCI can re-route an entire set of WDM channels from one core to another in the propagation direction. The DCI comprises a rectangular waveguide (WG) with an optimum GI profile in order to minimize intermodal dispersion along the device. Simulations of the proposed DCI device are performed using both finite-difference-time-domain (FDTD) and eigenmode expansion (EME) methods. The simulations verify the device operation and help optimizing its design in addition to assessing its performance. The DCI shows a high coupling-factor with negligible back-reflection, return-loss, and output cross-talk. To the best of my knowledge, this is the first time to report on such in-fiber data interchange device among cores of MCFs.

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2. Principle of operation

A homogeneous MCF consists of identical step-index single-mode cores arranged within same clad. The cores are sufficiently separated from each other to reduce crosstalk [7,8]. There are various MCF designs with different core numbers and arrangements. For example, MCF with 7, 12, or 19 cores in triangular-lattice, rectangular-lattice, or double-ring patterns were reported [7,8]. The most widely used MCF design is the identical step-index 7-cores in a triangular-lattice arrangement, as shown in Fig. 1a. This MCF design is used throughout the work here with the following parameters: Core diameter = 9 μm, clad diameter = 125 μm, adjacent cores separation = 40 μm, clad refractive index = 1.45, and relative refractive index difference = 0.35% [7,8]. Thus the calculated core refractive index is ≈1.4551.

Fig. 1a shows a MCF with one example arrangement of two DCI devices configurations. In DCI-2 × 2, the data interchange occurs between any two selected adjacent cores. The 2 × 2 DCI in Fig. 1a exchanges data between the input cores ports 6 and 7. In configuration DCI-3 × 3, the interchange occurs between any two selected cores that are separated by a third center-core on same plane of the two cores. The 3 × 3 DCI configuration in Fig. 1a allows data interchange between input cores at ports 2 and 5, without affecting propagating data on input center core at port 1. It is worth mentioning that although the DCI device here is applied to 7-core MCF as an example, it could be used with other designs of homogeneous step-index single-mode MCF configurations that have other core lattice arrangements.

Fig. 1b and c show the 2 × 2 and 3 × 3 configurations of the proposed DCI device, respectively, together with their 3D GI profiles. The DCI device is designed such that it consists of a rectangular waveguide enclosing two interchanged cores together with the clad spacing between them. The WG has a graded refractive-index across the device width. However, The GI is constant along the WG length and height, as shown in Fig. 1b and c. The GI profile is chosen to be parabolic with a peak refractive-index (1.4644) at the middle of WG width. This parabolic GI distribution is supposed to be the optimum profile to minimize intermodal dispersion [9] of propagating data along the WG. The WG width is selected such that the parabolic profile has a value equals to the cores refractive-index (1.4551) at cores outer-edges, as shown in the figures. However, the GI profile reaches a value equals to the clad refractive-index (1.45) at the WG side-walls. That makes the WG width slightly larger than the cores separation, and thus ensures that the rise and fall of GI-profile at outer-edges of cores are monotonic without any discontinuities. The calculated WG width is 61 μm in case DCI-2 × 2 configuration, and 110.24 μm in case of DCI-3 × 3 configuration. For both DCI configurations, the WG height is selected to be 10 μm to enclose the cores, while its length is optimized for best performance as discussed later.

3. FDTD simulations

The FDTD simulations of electric field magnitudes are performed using Lumerical software [10] to verify the DCI device operation and assess its performance. Although, MCFs are commonly used in the C-band because of low-attenuation, the WDM transmission might be extended in future MCFs networks over the S, L, or U bands as in case of SMFs nowadays. Therefore, FDTD simulations here are extended over the S, C, L, U bands (λ = 1.46–1.675 μm) to test the broadband operation of the DCI device.

Fig. 2a shows the FDTD simulation of DCI-2 × 2 with signals on one input core. Once the input beam emerges from input core into the GI waveguide region, it experiences total internal reflection (TIR) [9] near the WG side-wall and starts deflecting toward WG center. When it reaches the other WG side-wall, the other core collects beam power once it makes another TIR. Therefore, the beam is re-routed across the space between the two cores. It is found that

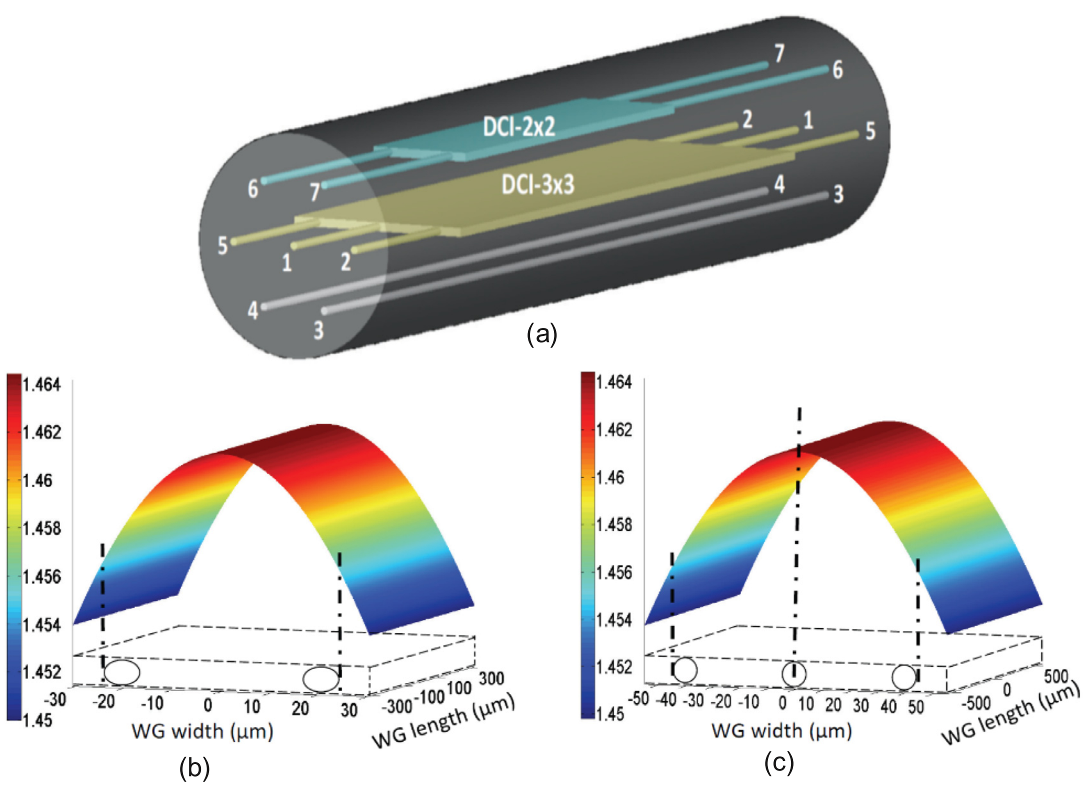

Fig. 1. (a) The 3D schematic of 7-core MCF with example arrangement of two DCI device configurations. The 3D graphs of parabolic GI profile together with the DCI configurations schematic: (b) the DCI-2 × 2, (c) The DCI-3 × 3.