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Compact in-fiber mode adapter based on double-cladding fiber for multimode fiber access networks

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ABSTRACT

A simple method for coupling light from a laser diode (LD) to multimode fiber (MMF) by using a compact in-fiber mode adapter, which is constructed with double-cladding fiber is presented, for the first time. Strong cladding-mode resonance across the thin-thickness inner cladding is used to excite the cladding modes. Principle of proposed mode adapter is theoretically investigated and its performances are experimentally verified by measurement results. By comparing the direct connection between LD and MMF, the coupling efficient of transmission power is improved by using our proposed adapter.

1. Introduction

The growth of bandwidth-intensive applications such as HDTV, IPTV, and data processing for other multimedia applications has resulted in a high demand for capacity of access networks and server interconnects [1,2]. MMFs are widely used in local area networks (LANs) and optical Ethernet backbones. Traditionally, as indicated previously, MMF is considered as the medium for short-reach applications. Nevertheless, it is important to note that MMF has several advantages in optical access networks such as easy installation, maintenance, and handling, which lead to low cost and the effective cross-sectional area of MMF is much larger than that of single mode fiber (SMF), which means much better tolerance to fiber nonlinearities and bending losses [3–6]. Thus, more power can be allowed to couple into the transmission fiber and this can further improve the system power budget.

Due to short range and cost sensitivity, many of the installed optical access networks are based on MMFs and operate at data rates of approximately 1 Gb/s. By means of some new technical methods, such as polarization multiplexing [7], optical orthogonal frequency division multiplexing [8] etc., a great deal of research is devoted to upgrading a large number of these installed optical access networks to 10 Gb/s and beyond [3].

However, one of the preconditions of above application is using laser diode (LD) instead of light emitting diode (LED) as the light source. Considering the extreme small light spot and emission angle, manufacturing defects of MMFs, direct coupling between LD and multimode fiber often leads to massive power loss and increases the effect of intermodal dispersion [9]. Fiber mode conversion has been studied widely, such as using two-dimension photonic crystals [10], using rectangular-core optical fibers [11], using grating-coupled multimode waveguides [12], etc. An expensive mode conditioning patch cord is usually inserted between LD and multimode fiber to alleviate such impairment in practical applications. In this report, we theoretically and experimentally demonstrate a simple and compact method for coupling light from a laser diode to multimode fiber by using an in-fiber mode adapter, which is constructed with double-cladding fiber (DCF).

2. Method and analysis

Based on SMF-DCF-MMF structure, we integrate the fiber mode adapter into one single fiber, namely in-fiber mode adapter. As depicted in Fig. 1, it is constructed by splicing SMF and MMF with one single appropriate length of DCF between them. Here the DCF can be seen as an optical coupler, whose core and inner cladding serves as two optical paths. Relative index (RI) profile of the DCF is depicted in Fig. 2. The core and out cladding layer has the same RI, which is a little higher than that of the inner cladding ($n_1 = n_3 > n_2$) [13]. Based on mode coupling theory [14], the core and cladding mode interact through supermode coupling in the DCF. The power ratio between core mode and cladding mode are equal if the suitable length of DCF is chosen.

Based on the mode analysis of depressed cladding structure [14], the double-cladding fiber is a typical leaky waveguide, i.e., core mode wave will tunnel out through the inner cladding layer at phase-matching wavelengths. The total energy of all stimulated modes in DCF is equal to input optical power as long as the input

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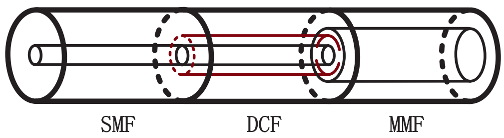

Fig. 1. In-fiber mode adapter constructed by DCF.

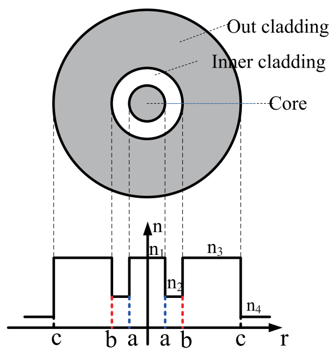

Fig. 2. Cross-section view for relative index profile of DCF.

light restricted in the core of DCF at injection point. It can be calculated by integral to the mode field. To understand the dynamics of light evolution in DCF, we expand the fundamental mode of SMF as the sum of modes of DCF. We calculated the energy distribution of DCF with $n_1 = n_3 = 1.456$, $n_2 = 1.4536$, $a = 4.6$ µm, $b = 13$ µm, $c = 62.5$ µm and noticed that the lower 10 modes in DCF accounted for most of field energy especially the mode LP_{05} and LP_{06} as indicated in Fig. 3. The sum of these two modes has 92% energy of the input power. Consequently simplifying the propagation analysis, the superposition of the mode LP_{05} and LP_{06} can be used to approximate the exact energy distribution.

At injection point of DCF, there is no phase difference between mode LP_{05} and LP_{06}, total energy is the sum of above two modes and restricted in fiber core. After a propagation distance of $L_B \approx \pi/(\beta_{05} - \beta_{06})$, namely a beat length, the phase difference between two modes reaches π and total energy is coupled to the fiber cladding. Where β_{05} and β_{06} are the corresponding wave vectors of mode LP_{05} and LP_{06}. The field distribution at the input and beat length, are shown in Fig. 4(a) and (b), respectively.

Lights emitted from a LD can be first collimated into the SMF easily. Consider the mode field diameter of the inner cladding is close to the core of MMF, more power can be coupled into MMF compare to the direct connection of LD and MMF. This fiber mode adapter is cheaper than using mode conditioning patch cord and easier to handle than using photonic crystals or other type of waveguide, especially in large scale optical access networks. To verify the prediction, we calculate the optical power distribution along

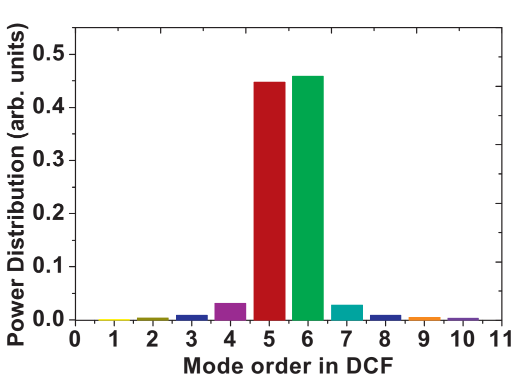

Fig. 3. Power distribution of excited modes in DCF.

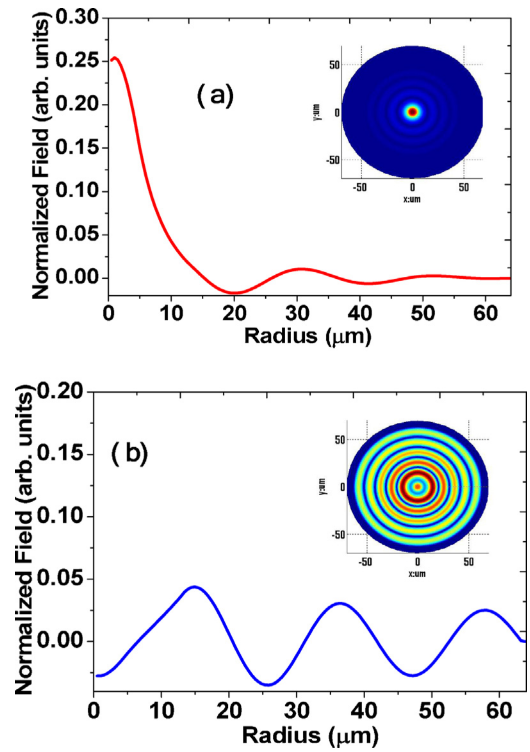

Fig. 4. Field distribution of sum of LP_{05} and LP_{06} modes (a) at the input point and (b) at beat length point.

the coupling area with and without using proposed fiber mode adapter with 1 cm DCF at 1550 nm and 1310 nm, respectively. During the transmission, DCF serves as the optical coupler and couple more power to MMF as demonstrated in Figs. 5(b) and 6(b) compare to the direct connection in Figs. 5(a) and 6(a), Figs. 5(b) and 6(b). Coupling efficiency is obviously increased.

3. Experimental results and discussions

Through the conventional modified chemical vapor deposition (MCVD) technique, the core and out cladding layers of proposed DCF are made of pure silica and the inner cladding is made of fluorine-doped silica. Refractive index profile of DCF is measured

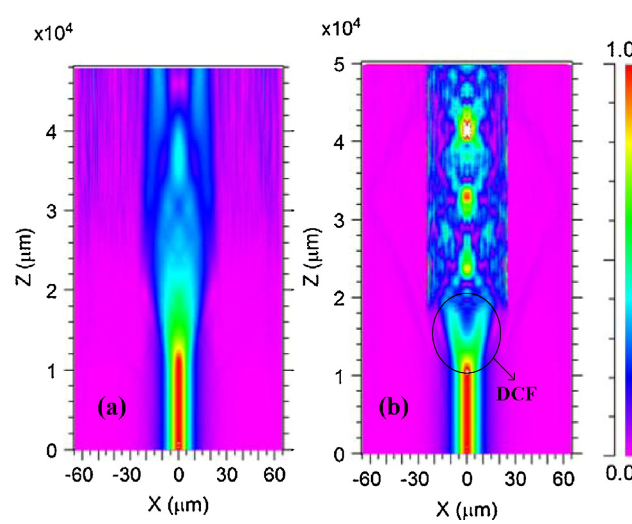

Fig. 5. Power distribution along the coupling area at 1550 nm (a) by using direct connection (b) by using fiber mode adapter.