Long-period grating based single-mode fiber to multi-core fiber pump coupler

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Abstract: We theoretically demonstrate a long-period grating (LPG) based single-mode fiber to multi-core fiber coupler. The coupling efficiency achieved was 24% of the input power, evenly distributed by all cores, using LPGs of length 4 cm.

1. Introduction

Spatial division multiplexing (SDM) has been pointed out as viable candidate to solve the imminent optical networks exhaustion [1]. SDM using weakly-coupled single-mode multi-core fiber (MCF) is the option in which is simpler to achieve large capacity over long-distance transmission [1]. The cost-effectiveness of SDM transmission systems will depend on the reduction of the overall cost and the power consumption of the transmission systems. Hence, it is mandatory to reduce the number of components, by developing component sharing based devices. In this way, multi-core optical amplifiers that are able to amplify all the channels by sharing a single pump source are indispensable. One approach is based on a double-cladding pumping scheme, however, the pump efficiency is low due the small overlap between the cores and the pump mode. In fact, it was estimated that the MCF cores absorb about 15% of the power coupled into the MCF cladding [2].

Long-period gratings (LPGs) are induced periodic perturbations on the optical fiber refractive index, with periods in the range of 100 µm up to 1 mm, that induce coupling between modes traveling in the same direction at the resonant wavelength [3]. LPGs have already been proposed for several applications for optical communications. And LPG based couplers between two single-mode fibers (SMFs) were already experimentally demonstrated [4]. In MCFs, an LPG based scheme to distribute a single pump launched in one core of an MCF to all the other ones was demonstrated with promising results [3, 5]. However, this technique still needs an expensive fan-in fan-out to launch light into one core. Here, we propose an LPG based technique to couple the light from an SMF to all the cores of an MCF without the need of an expensive fan-in fan-out (SMF to MCF coupler).

2. SMF to MCF coupler analysis

Figure 1a displays the scheme of the proposed coupler, it consists in an SMF and an MCF next and parallel to each other, with LPGs inscribed on it. The light launched into the SMF core is transferred to the SMF cladding due to the inscribed LPG. The light from the SMF cladding mode is transferred to the MCF cladding mode by evanescent field. In the MCF, the optical power at the cladding is evenly distributed to each MCF core due to the identically LPGs inscribed in them. Since LPGs are designed to match the pump source wavelength, the remaining transmitted signals will not be affected. To enhance the power transfer between the fibers, we assumed the fibers surrounded by an index-matching gel and a standard SMF with a reduced cladding radius was considered [4]. Reducing the cladding radius (e.g., by etching the SMF) will enhance the evanescent field of the cladding modes [4].

We used the coupled-mode theory to study the energy transfer between the optical modes. The evolution of the optical signal with slowly varying amplitude A_p along z can be given by [6]:

$$\frac{dA_p}{dz} = i\sum_q A_q(z)\kappa_{qp}\exp[i(\beta_q - \beta_p)z] \tag{1}$$

where A_q is a slowly varying amplitude of the mode q, κ_{qp} is the transverse coupling coefficient between modes q and p, and β_q and β_p are the propagation constants of the mode q and p, respectively. κ_{qp} is given by [3, 6, 7]:

$$\kappa_{qp} = K_{qp} + C_{qp} = \frac{\omega\varepsilon_0 n_c \delta n\left[1+\cos\left(\frac{2\pi}{\Lambda}z\right)\right]}{2}\iint\limits_{\text{core}} \boldsymbol{E}_q\cdot\boldsymbol{E}_p^* \,dx\,dy + \frac{\omega\varepsilon_0(n_{cl}^2 - n_e^2)}{4}\iint\limits_{\text{cladding}} \boldsymbol{E}_q\cdot\boldsymbol{E}_p^* \,dx\,dy \tag{2}$$

being ω the angular frequency of the light, ε_0 the vacuum permittivity, n_c the core refractive index, δn the index modulation amplitude, Λ the LPG period, $\boldsymbol{E}_q$ and $\boldsymbol{E}_p$ the normalized electric field of the mode q and p, respectively, and n_{cl} and n_e the cladding and index-matching gel refractive index, respectively. In Eq. (2), κ_{qp} is assumed as the sum of two types of coupling coefficients, that differ from each other on the nature of the perturbation to the electric permittivity: K_{qp} is due to the LPGs inscription and C_{qp} is due to the evanescent field.

The optical modes were calculated using the Wave Optics module of the software package Comsol Multiphysics®. The parameters of the considered SMF and 4-core fiber (4C1500(8.0/125)/001 from Fibercore) are summarized in Fig. 1a and the index-matching gel refractive index is n_e =1.4386 (Thorlabs G608N3 index-matching gel). In both LPGs, a $\delta n = 5 \times 10^{-4}$ was considered. The light wavelength is 1480 nm, the typical wavelength for Raman amplification. We then chose the pair of cladding modes that presented higher coupling between them, hence an SMF with a reduced cladding radius to 59 µm was considered. The effective refractive index of the cladding modes used are 1.443383 (SMF) and 1.443386 (MCF). The LPGs periods were calculated as in [6], attaining periods of $\Lambda_S = 402$ µm and $\Lambda_M = 268$ µm.

Figure 1b displays the modes power evolution along the fibers. The light launched in the SMF is transferred to its cladding and, then, to the MCF cladding. The power in the MCF cores increases at the same rate, which leads to an even distribution of power among them. It was achieved a maximum power transfer from the SMF to the MCF cores of -6 dB (24% of the input power), -12 dB (6% of the input power) per MCF core, with an LPG length around 4 cm.

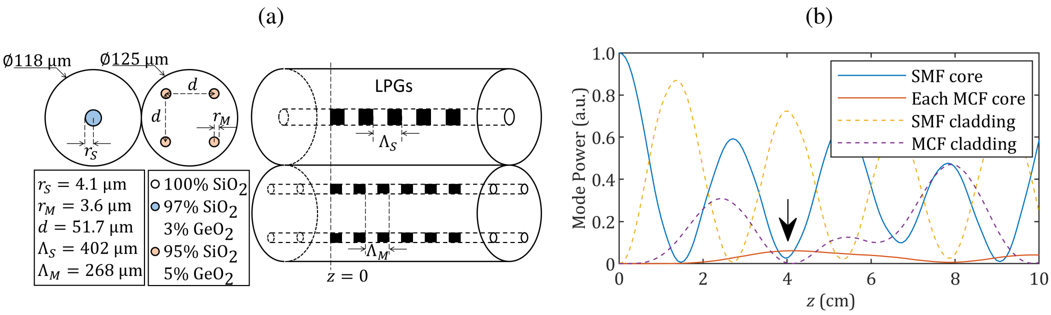

Fig. 1. (a) Scheme of the proposed SMF to MCF coupler (with the claddings and cores dimensions and material) and (b) normalized mode power evolution along z, at a wavelength of 1480 nm.

3. Conclusion

The proposed device is able to evenly distribute a single pump source injected in an SMF core to all the cores of a 4-core fiber. It was achieved a maximum power transfer of 24% (-6 dB), 6% (-12 dB) per MCF core, using LPGs with 4 cm of length. Although the coupling efficiency of the proposed device still needs further enhancements, this study paves the way to produce LPG-based SMF to MCF couplers for SDM transmission systems.

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