Analysis of the coupling between a single-mode fiber to a multi-core fiber with long-period gratings

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***Abstract*—In this paper, the coupling of a single source injected in a single-mode fiber to all the cores of a multi-core fiber is theoretically studied. The power transfer between the core and the cladding of a fiber is promoted by long-period gratings. To promote the power transfer between the fibers, we considered cladding modes with similar effective refractive index. The results show that the coupling is possible, but the design still needs to be optimized to maximize the power transfer.**

***Index Terms*—multi-core fibers, spatial division multiplexing, long-period gratings, coupler, coupled-mode theory**

I. Introduction

The conventional optical fiber communications systems are approaching their technological limit while the demand for data is increasing exponentially [1], [2]. It is anticipated that, by 2020, transmission capacity will reach the theoretical limit over a single-mode fiber (SMF) of 100 Tb/s [3]. During the past years, the capacity of a single-mode fiber has increased due to the use of several multiplexing technologies, such as time division multiplexing (TDM), wavelength division multiplexing (WDM) and digital coherent technologies [4]. Now, new multiplexing techniques are needed to deal with the demand of data. They should offer an additional multiplicity of around ten to a hundred times and compatibility with current systems [4]. A proposed solution is space division multiplexing (SDM), based on few-mode fibers and/or multi-core fibers (MCFs). Although each MCF core should be subject to similar capacity limitations as a conventional single-core fiber [1], the additional cores are used as another channels to deliver more data through a single fiber. In terms of transmission, a capacity of 10.16 Pb/s was already achieved over a 6-mode 19-core fiber [5].

However, not only the transmission capacity is important. The compatibility with existing systems and the reduction of cost and power consumption of the integrated SDM technologies are some of the aspects that also need to be considered in the upgrade from conventional systems to future SDM networks [2].

Several MCF devices have been demonstrated, such as multi-core erbium doped fiber amplifiers [1]. But these devices cost and efficiency have yet to improve [1]. One approach in the development of efficient optical amplifiers is component sharing over multiple cores [1], e.g., using the same pump source to amplify all the cores of a MCF. A cladding pumping scheme was already proposed [6], but the pump efficiency is low due to the large effective mode area of the cladding and small overlap between the cores and the pump power mode [7]. Another technique, that uses long-period gratings (LPGs), to distribute a single source injected in one core to all cores of a MCF was demonstrated with promising results [8]–[10]. However, a SMF to MCF coupler would be mandatory, since it will avoid the use of an expensive fan-in/fan-out to launch light into the MCF.

In this work, we theoretically studied a LPG based technique to couple a single source from a SMF to a MCF, parallel and touching each other. This technique distributes the power evenly to all MCF cores and, in this way, can be used to couple a single pump source from a SMF to all cores of a MCF.

II. Concept and analysis

LPGs are periodic gratings, with periods ranging from 100 μm to 1 mm, that promotes the coupling from the propagating core mode to forward-propagating cladding modes, at discrete wavelengths [8], [9]. Thus, a LPG inscribed in the SMF couples light from the core mode to the cladding mode, which, at the same time, couples to the cladding mode of the MCF through evanescent field. Then, the LPG inscribed in each MCF core will promote the coupling with the cladding mode and, if the LPGs are identical in all cores, an even distribution of power between them.

Here, we considered a SMF with one central core and a MCF with four cores at equal distance to the center of the fiber. The SMF core's radius is r_S and all MCF cores are identical with a radius r_M. The fibers are parallel and touching each other. It is assumed that the LPGs are inscribed in the cores of

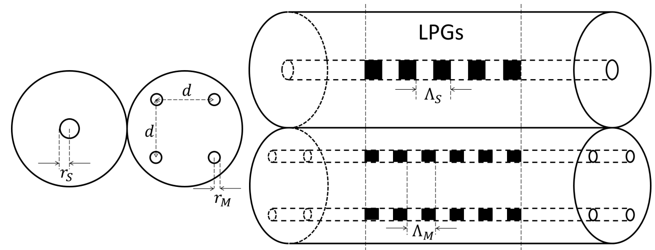


Fig. 1: Schematic diagram of the considered LPG based SMF-MCF coupler.

the fiber by a sinusoidal modulation of the core refractive index with period Λ_S (SMF core) and Λ_M (MCF cores) (Fig. 1).

The power coupling between forward modes based on the coupled theory is written as [11]:

$$\frac{dA_p}{dz} = i \sum_q A_q(z) k_{qp} \exp[i\Delta\beta_{qp} z] \tag{1}$$

where A_p is the amplitude of the mode p, z is the propagation direction, $\Delta\beta_{qp} = \beta_q - \beta_p = -\Delta\beta_{pq}$ is the propagation constants difference, being β_q and β_p the propagation constants of the modes q and p, respectively. k_{qp} is the coupling coefficient between modes given by [12]:

$$k_{qp} = \frac{\omega}{4} \iint_{\infty} \Delta\epsilon \boldsymbol{E}_q \cdot \boldsymbol{E}_p^* dxdy \tag{2}$$

being ω the angular frequency of the light, $\Delta\epsilon$ the perturbation to the permittivity and $\boldsymbol{E}_q$ and $\boldsymbol{E}_p$ the normalized electric field of the modes q and p, respectively. $\Delta\epsilon$ is given by [13]:

$$\Delta\epsilon = \epsilon_0 \Delta(n^2) \tag{3}$$

where ϵ_0 is the vaccum permittivity and n is the refractive index. Since k_{qp} depends on the perturbation nature, we considered two types of coupling coefficient: when the refractive index difference is due to the LPGs inscription (K_{qp}) and when it is due to the presence of the other fiber (C_{qp}).

The LPG inscription introduces a refractive index difference in the core, which is much lower than its refractive index. Applying the approximation $\Delta(n^2) \approx 2n\delta n$ when $\delta n \leqslant n$ [12], the coupling coefficient for the considered LPGs is given by [11]:

$$K_{qp} = \sigma_{qp}(1 + \cos(\frac{2\pi}{\Lambda} z)) \tag{4}$$

with

$$\sigma_{qp} = \frac{\omega\epsilon_0 n_c \delta n}{2} \iint_{core} \boldsymbol{E}_q \cdot \boldsymbol{E}_p^* dxdy \tag{5}$$

being Λ the LPG period, n_c the core refractive index and δn the index modulation amplitude.

LPG promotes the coupling between core modes and forward-propagating cladding modes at a resonant wavelength, which is given by [11]:

$$\frac{1}{\lambda \text{max}} = (\frac{\sigma_{clcl} - \sigma_{cc}}{2\pi} + \frac{1}{\Lambda})/(N_c - N_{cl}) \tag{6}$$

where N_c and N_{cl} are the mode effective refractive indices and σ_{cc} and σ_{clcl} are the self-coupling coefficients for the core and cladding modes, respectively.

If the fibers are close to each other, the coupling between their cladding modes will be promoted by evanescent field. In this case, i.e., in the coupling between cladding modes of different fibers, we considered that the coupling coefficient depends on $\Delta(n^2) = n_{cl}^2 - n_e^2$ [14] and is given by:

$$C_{qp} = \frac{\omega\epsilon_0(n_{cl}^2 - n_e^2)}{4} \iint_{fiber_p} \boldsymbol{E}_q \cdot \boldsymbol{E}_p^* dxdy \tag{7}$$

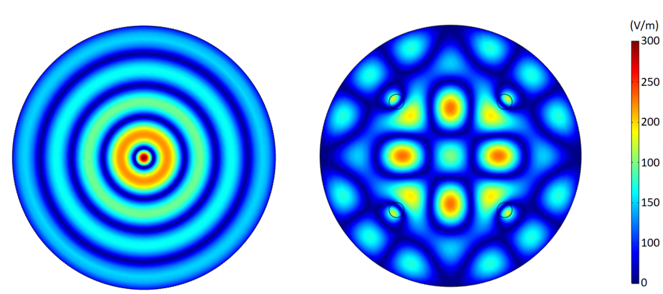
where n_{cl} is the cladding refractive index and n_e is the refractive index of the region outside the fibers, which we considered as a gel to increase the power transfer between the fibers.

III. Results

We calculated the mode power evolution in SMF and MCF through integration of the system of coupled mode equations (1), using a Runge-Kutta method. The electric field distribution ($\boldsymbol{E}$) and the effective refractive indices (N) were obtained using the software package Comsol Multiphysics® with the Wave Optics module to solve the vectorial Helmholtz equation for each bare fiber in a index matching gel with a refractive index of 1.4378 at a wavelength of 1550 nm (Fig. 2).

We considered a SMF that has one core with radius of $r_S = 4.1$ µm and a MCF that has four cores with radius of $r_M = 3.6$ µm and they are equally separated by a distance $d = 51.7$ µm. The cladding radius of both fibers is $r = 62.5$ µm. The fibers material is assumed to be pure silica in the cladding and GeO_2 doped silica in the cores. We considered a GeO_2 concentration in the SMF core of 3% and in MCF cores of 5%. The refractive indices are defined by a Sellmeier equation as in [15]. At a wavelength of 1550 nm, the refractive indices of the claddings, SMF core and MCF cores are 1.4440, 1.4485 and 1.4515, respectively. We considered LPGs in all cores inscribed in the same longitudinal position (z) and with an index modulation amplitude of $\delta n = 5 \times 10^{-4}$.

We considered one mode for each core and one cladding mode for each fiber. The cladding modes chosen have the same



(a) (b)

Fig. 2: Distribution of the electric field norm (V/m) of the chosen cladding mode at the wavelength of 1550 nm in SMF (a) and MCF (b).

TABLE I: Effective refractive indices of each mode.

#	Modes	N
1	SMF core	1.4457
2-5	MCF cores	1.4459
6	SMF cladding	1.4431
7	MCF cladding	1.4431

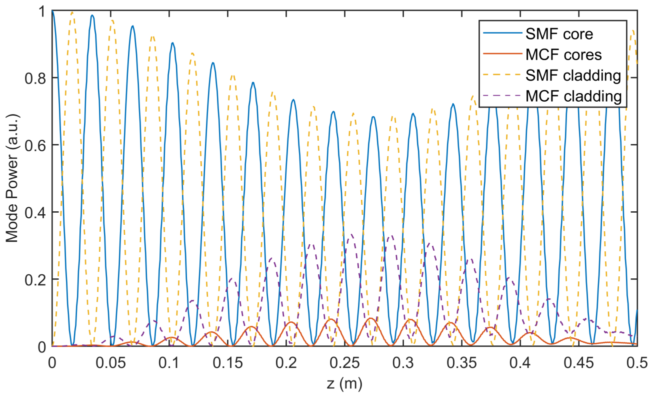


Fig. 3: Normalized mode power evolution along z at a wavelength of 1550 nm.

azimuthal symmetry of the core fundamental mode, because when we use gratings with symmetric index changes, like the ones we are considering, the coupling just occurs for modes with the same azimuthal symmetry [12]. In addition, we chose cladding modes with similar effective refractive indices to increase power transfer between them. Their electric field distributions are displayed in Fig. 2. The effective refractive indices calculated for each mode are in table I.

In order to achieve maximum coupling between the SMF core and cladding and then between the MCF cladding and cores, we calculated the LPG period as in (6), attaining periods of $\Lambda_S = 518.70$ µm and $\Lambda_M = 493.99$ µm, for a resonant wavelength of 1550 nm.

Fig. 3 displays the power evolution with z in the two fibers, considering the light is launched into the SMF core. The power carried by the SMF core is transferred completely to the cladding and vice-versa, periodically. During this process, part of the power of SMF cladding is transferred to MCF cladding. In the MCF, the cladding power is then transferred evenly to all cores. The maximum power achieved in the MCF is -11 dB on each core at a LPG length of 0.27 m.

IV. Conclusions

The coupling between a SMF to a MCF is theoretically demonstrated. Each core of the MCF achieved a maximum power of -11 dB at a LPG length of 0.27 m.

The results presented here are initial results, and constitute a first step in the development of a SMF-MCF coupler. The coupling can be optimized by using other cladding modes, that promote more power transfer between fibers, optimizing the lengths and period of the LPGs, inserting an offset distance between the SMF and MCF LPG longitudinal position and using other types of fibers in order to achieve total power transfer among cores.

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