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State-of-the-art multicore fiber amplifiers for space division multiplexing

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ABSTRACT

Space division multiplexing (SDM) has generated much interest lately as a potential means for enhancing the capacity of optical transmission systems. During the past several years, we have observed tremendous research efforts in the development of SDM amplifiers with an aim to increase core and mode counts and to improve amplification properties and pump conversion efficiencies. We report on the recent development of multicore fiber amplifiers suitable for amplifying space division multiplexed signals. Multicore fiber amplifiers with different number of cores, and pumping schemes have been developed to pump the cores individually or through a common cladding. We will report on the structures of SDM amplifiers, their optical properties, and discuss prospects for further development.

1. Introduction

It has been realized lately that various technologies developed for enhancing the transmission capacity in conventional single mode fibers are not adequate to deal with the ever-increasing need for bandwidth [1,2]. Instead of deploying additional single mode fiber to provide more bandwidth, which may seem to be a straight forward solution, other more ingenious schemes have been pursued around the globe to solve this problem. One approach which has drawn widespread interests is space division multiplexing (SDM). It relies on sending data through multiple cores embedded into a single strand of fiber or using multiple transverse modes supported by a core [3,4]. The stimulus behind pursuing SDM involves reducing size through integration, reducing power consumption, and minimizing the cost of deployment and operation. Different forms of high-performance multicore fibers, few-mode fibers, as well as their combination (few-mode/multicore) fibers have been proposed and fabricated, and have been proved to be useful for enhancing the transmission capacity by over an order of magnitude [5–9].

As in conventional transmission systems, optical amplifiers that can compensate for attenuation of signals in the SDM transmission links will be of paramount importance [10–14]. Stimulated by the first demonstration of a 7-core, erbium-doped, fiber amplifier [10] and a multimode amplifier designed for SDM application [11,12] in 2011, much efforts has been put forth in amplifier development aiming to provide low-cost, energy efficient, and integrated solutions [15–28]. Multicore, few-mode amplifiers with different core and mode counts combined with numerous approaches for efficient coupling signal and combining pump have demonstrated great potential in the areas of SDM.

In this paper, we report on the recent advancement made in the development of multicore erbium-doped fiber amplifier's (MC-EDFA). We will describe the different gain fibers and other key components developed for coupling signal and pump light under varying pumping architectures. We will present the amplification and noise properties of various core- and cladding-pumped MC-EDFAs and also discuss prospects for multicore fiber amplifiers.

2. Multicore rare-earth doped fiber

Multicore fiber amplifiers for SDM employs gain fiber with multiple cores, each doped with erbium ions in order to provide gain to signal around 1.55 μm. These cores are typically arranged in a periodic hexagonal pattern and surrounded by a glass cladding. These cores are separated sufficiently so that electric field of signal within one core interferes minimally with the field of the neighboring core. Such uncoupled cores can be treated as separate entities. In order to establish population inversion and thus gain, the cores are pumped at suitable wavelengths, typically at 980 nm or 1480 nm. Multicore amplifiers can be pumped mainly in two ways; one is "core pumping", where the cores are pumped separately by launching single mode pump radiation in either the forward, backward or both directions. The second approach is called "cladding pumping"; where all cores are being pumped simultaneously using

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multimode pump light launched through cladding. The cores are often co-doped with ytterbium in order to increases pump absorption, which is often desirable for efficient utilization of pump in a relatively short length of fiber and is particularly suited for cladding pumped amplifier.

In conventional core-pumped, erbium doped, fiber amplifiers, the core diameter and the numerical aperture are chosen so that single mode propagation is ensured for both pump and signal wavelengths. For example, the commercially available OFS-EDF MP980 has a core diameter of 3.2 μm and a NA of 0.23, which gives V-number of 1.49 and 2.359, for 1550-nm-signal and 980-nm pump, respectively. In a cladding pump amplifier the pump is multimoded; therefore the core diameter can be enlarged further to support the fundamental signal mode. For example, core diameter can be increased to ~5.2 μm for the same NA while still ensuring single mode operation at 1550 nm. Such enlargement of the core size can help increase multimode pump absorption (proportional to the ratio of cross-sectional areas of core to cladding) and enhance amplifier saturation power. Moreover, by increasing the core-size further to support a few higher order modes, we can amplify multiple modes simultaneously using the same pump source, which is potentially useful for enhancing transmission capacity.

When a multimode pump is launched into a fiber with cylindrical surface, it excites certain modes that propagate like helical rays which have no overlap with a core that is located at the center. Those modes remain unabsorbed, which results in unequal, pump distribution. Such modes with poor overlap are avoided by breaking the structural symmetry, such as by choosing off-centered core or by choosing non-cylindrical cladding surface like D-shape or star shape. However, in a multicore fiber amplifier, even when the cladding is cylindrical, pump distribution is found to be uniform across the cladding. The off-centered cores close to the cladding surface are expected to play a role in preventing the formation of such modes and promote better mixing of modes resulting in uniform pump distribution. Recently, evolution of distribution of multimode pump in multicore double clad fiber has been studied using beam propagation method (BPM), which showed that the injected pump power gets rapidly distributed across the cladding after a propagation length as short as 3 cm [27].

In order to achieve high gain and low noise figure, it is desirable to minimize the cladding size, and to choose a close-packed lattice for the cores. Ultra-low-crosstalk 7-core fiber with core-to-core pitch of 45 μm and cladding diameter of 150 μm for long-haul transmission has been realized, in which the mean crosstalk between neighboring cores were measured to be less than −77.6 dB for λ = 1550 nm in a 17.6-km-long fiber [29]. Since, the length of gain fiber used in amplifier is less than a hundred meters, there is scope for further reduction in core-to-core without introducing significant amount of crosstalk between the cores.

Recently, a multicore fiber with annular cladding has been proposed to increase the pump intensity [27,28]. In this structure the cores are located within the annular region. The inner circular region is either hollow or comprised of glass with lower refractive index, which causes pump light to be confined in the annular region. This ensures higher pump intensity, though at the expense of a reduction in core count proportional to the area of the low-index circular region.

Fig. 1(a) and (b) show the cross-sections of a 7-core EDF we made for core-pumped and cladding-pumped amplifiers, where the cores are arranged in a hexagonal array with a ~41 μm pitch [10]. The core diameter and numerical aperture were equal to 3.2 μm and 0.23, respectively. The mode field diameter (MFD) at 1550 nm was about 6 μm. The erbium-doped core has an absorption coefficient of ~2.3 dB/m at 1550 nm. The multicore fiber for core pumping had a cladding diameter of 148 μm, and for cladding pumping the fiber clad diameter was reduced to 100 μm in order to increase the intensity of pump and was coated with low-index polymer coating (~NA: 0.45) for guiding multi-mode pump light. In the double clad 7-core EDF, the thickness of the cladding region beyond the outer cores was ~15 μm, and for a coil diameter of 20 cm, the bending loss in 50-m-long gain fiber were found to be negligible.

Fig. 1(c) shows cross section of Er/Yb co-doped 12-core fiber, as reported in Ref. [26], where cores are arranged in the form of a hexagon with an average pitch of 36.6 μm [26]. Core count has been increased further by incorporating additional layer/ring of cores. Reference 19 reports on a multicore core-pumped EDFA that has 19 cores (MFD: 6.6 μm) arranged in three layers within a cladding size of 220-μm. Cross section of a 19-core EDF is shown in Fig. 1(d). Multicore erbium doped fiber with larger core-size supporting few-modes has also been reported recently. Fig. 1(e) shows schematic of an Er doped fiber with 6-cores, each supporting 3 modes (LP_{01}, LP_{11a} and LP_{11b}) [28]. The cores are embedded within an annular cladding region and the distance between two neighboring core was 62 μm. The outer and inner diameters of the annular cladding are 170 μm and 85 μm, respectively. The NA between the core and annular cladding is 0.104, and the NA between the annular cladding and inner circular cladding is 0.11. The inner circular region has lower index than cladding, causing the multimode pump radiation to be confined within the annular region.

3. Signal/Pump coupler for MCFA

It is desirable that spatially multiplexed signal from passive multicore transmission fibers be directly launched into the multicore gain fiber without de-multiplexing into separate channels. Currently, however, in the absence of suitable optical components (e.g., WDM, isolator, gain flattening filter, tap-coupler) with proper multicore fiber pigtails required for building fully integrated SDM system, fan-in and fan-out devices are being used for getting access into individual cores. Various fan-in, fan-out devices have been proposed, which includes all-fiber based tapered fiber bundled (TFB) coupler [10,20], bulk-optics couplers [30], reduced-cladding bundled coupler [18], as well as 3-D waveguide based coupler.

For amplifying applications, single mode pump radiation can also be added to the signal simply by using commercial fiberoptic wavelength division multiplexers (WDM), before launching into the coupler.

3.1. Couplers for core pumping

Tapered fiber bundle (TFB) coupler-based, fan-in/-out devices for core pumping are created by tapering adiabatically a bundle of specially designed single mode fibers by a predetermined ratio so that the core-to-core pitch at the tapered end matches with that of the MC-EDF. Each strands of the fiber bundle could be spliced to separate SMF fibers with low loss. Moreover, at the tapered end, the MFD matches well with that of the MC-EDF. Fig. 2(a) and (b) show schematic and a photograph of the TFB coupler.

Bulk-optics based couplers consist mainly of multiple number of bulk-optic lenses that collimates signal from individual single mode fiber and a focusing lens that couples each of these collimated beams into respective cores of the multicore fiber [30]. A schematic is shown in Fig. 2(c). All the lenses and fiber end-facets are provided with broadband, anti-reflection (AR) coating in order to minimize feedback from glass-air interfaces. Coupling to as many as 19 cores in MCF has been already demonstrated using this approach [31]. One advantage of bulk-optic coupling approach is that it can provide room for incorporating other

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