Amplification of 12 OAM States in an Air-Core EDF

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Abstract: We propose the amplification of 12 OAM modes in an air-core EDF using either core- or cladding- pumping at 980nm. Differential modal gains of only 0.25dB among all the 12-modes are achieved over the C-band.

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1. Introduction

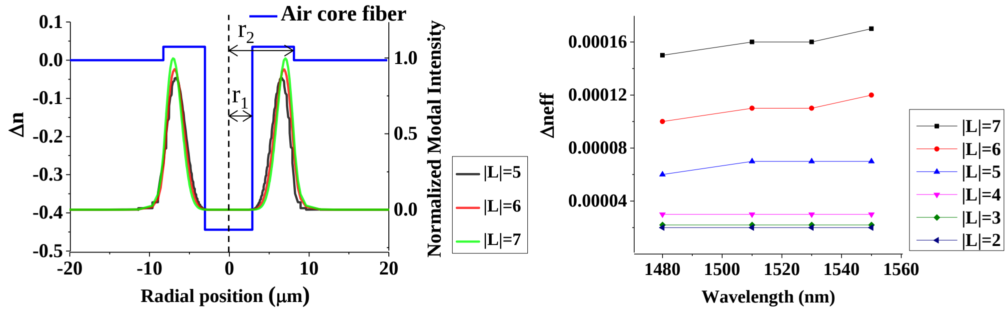
It is well known that photons can carry orbital angular momentum (OAM), characterized by a helical phase front, $\exp(iL\varphi)$, where L is the topological charge. Recently, the use of OAM states as orthogonal signal channels in communication systems has gained much interest [1-3]. To date, two classes of fiber have demonstrated OAM guidance. In the first class, based on solid core fiber designs (e.g. the vortex fiber [1]), transmission of low-order OAM states has been achieved. However, solid core fibers are typically incapable of transmitting higher-order OAM states, because either the fiber's effective V-number is not sufficient, or the vector splitting of the higher-order OAM states becomes small. The second class features an air core and an annular raised-index region which guides light [3,4]. The air-glass interface's high index-contrast enables large effective index splitting among the vector (HE/EH) modes of the same |L| family, even for high orders in L, which significantly reduces modal crosstalk and allows stable transmission of the high-order OAM states. Higher-order OAM states have also been theoretically postulated to have better tolerance to fiber ellipticity and birefringence [2] and experimentally demonstrated to resist bend perturbations [5], and hence appear suitable for long distance transmission. If such a scheme is to be applied in long haul transmission networks, then in-line OAM mode amplifiers will be essential. Similar to few-mode erbium doped fiber amplifiers (FM-EDFAs) used in few-mode transmission, the differential modal gain (DMG) for independent OAM modes will be a key characteristic of OAM EDFAs and must be minimized to optimize system performance.

In this work, we present modeling results on the amplification of 12 OAM modes (|L|=5, 6, 7 for all combinations of L and S, S representing spin) over the C-band in an air-core fiber using either core- or cladding-pumping at 980nm. Under core pumping condition, we found that pumping using the |L|= 8 OAM mode provides the lowest DMG of 0.25 dB among the signal |L|=5, 6 and 7 modes, whilst most other choices of pump modes would create a DMG >1 dB. Under the more desirable/ practical case of cladding-pumped operation, there is a ~2.5 dB gain difference amongst the signal modes when the annular ring core is fully doped. However, with an optimized erbium doping profile, we achieve exceptionally well equalized modal gain (DMG ≤0.25 dB) for all 12 OAM modes.

2. Modeling of the amplification of OAM modes in air-core fiber

Figure 1(a) shows the Refractive Index Profile (RIP) of the air-core fiber. The inner radius (r_1) of the air core is 3µm, the outer radius (r_2) is 8.25 µm and the refractive index difference between the annular guiding region and the silica cladding is 0.035. The air-core fiber is designed to guide up to the |L|= 7 OAM family. Here, the OAM modes are identified as $OAM_{(L,\,m)}$, where L is the topological charge, and m is the number of concentric rings in the intensity profile of the mode. The modal intensity profiles of $OAM_{(L,1)}$ |L|=5, 6 and 7 modes are shown in Fig. 1(a). Figure 1(b) shows the effective index difference between the vector modes (i.e. HE/EH modes) from the same |L| family (m=1) as a function of wavelength. Fig. 1(b) shows that a large effective index splitting is observed among the high-order OAM families (i.e. |L|= 5, 6 and 7), which makes these OAM modes more resilient to perturbations as they propagate along the fiber. The low-order $OAM_{(L,1)}$ modes (|L|=1 - 4) are not considered in this work due to the insufficient vector splitting. The double ring modes (i.e. $OAM_{(0,2)}$ - $OAM_{(3,2)}$) are also guided in the air-core fiber at 1550nm in principle, however, these modes are not considered in this work for two reasons. First, if the double ring modes become degenerate in some wavelength regime with the high-order ring modes, phase-matched cross-coupling is possible. Second, passive fiber coupling and transmission of such states has not yet been demonstrated.

The core-pumped OAM mode amplifier is simulated using the vector-mode FM-EDFA simulator described previously [6], for $OAM_{(L,m)}$ modes: $OAM^{\pm}_{\pm L,m} = HE^{even}_{L+1,m} \pm iHE^{odd}_{L+1,m}$ and $OAM^{\mp}_{\pm L,m} = EH^{even}_{L-1,m} \pm iEH^{odd}_{L-1,m}$ [7]. The vector fields of signal and pump modes are computed using COMSOL Multiphysics® software. In the cladding-pumped case, we treat the heavily multi-moded pump as a single transverse mode with uniform intensity across the inner cladding and annular guiding region [8]. Based on this, we adapt our vector-mode EDFA simulator to become cladding pump-able. For all the simulations in this work, we model the simpler case of a co-propagating pump, to speed up simulations and facilitate the exploration of a wider range of pump modes and design parameters.



(a) (b)

Figure 1. (a) The RIP of the air core fiber overlaid with the normalized signal intensity profile of the OAM states |L|= 5, 6, 7. (b) the effective index difference (Δneff) between the vector modes within the same |L| family as a function of wavelength, for radial order m=1.

3. Results and discussions

(1) Core pumped operation

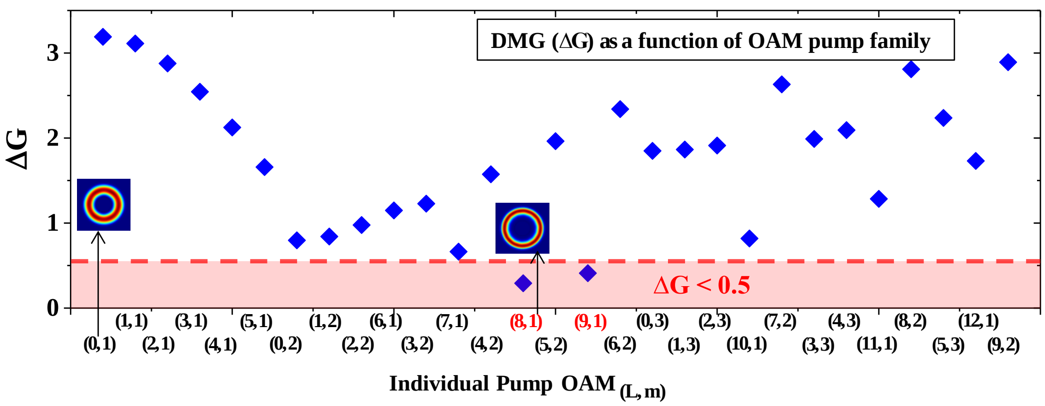
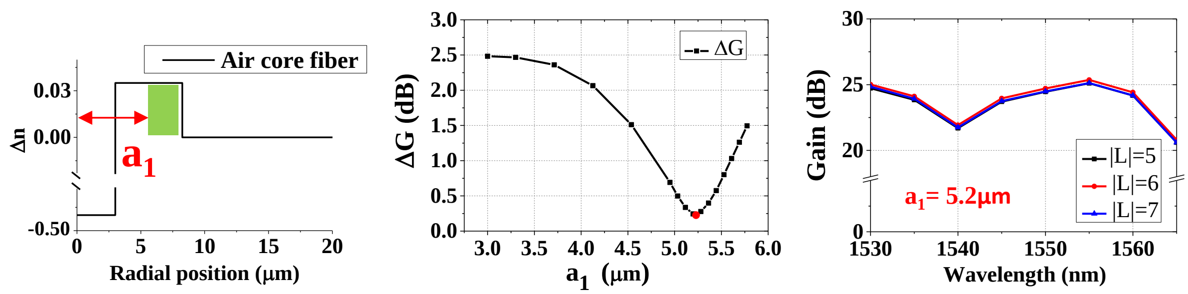


Figure 2. The distribution of DMGs and their corresponding pump $OAM_{(L,\ m)}$ used in the simulation.

At 980nm, this fiber guides 110 vector modes (including degeneracies), which can be grouped into 29 (L,m) OAM families and the $TM_{0,m}$, $TE_{0,m}$ modes. Each $OAM_{(|L|,m)}$ (|L|=0, 1) family has two OAM modes; and each $OAM_{(|L|,m)}$ (|L|≠0, 1) family has four OAM modes. In order to completely describe how each pump mode impacts the DMG, we assess the 110 pump modes individually. In each simulation run, only one pump mode is launched into the OAM amplifier. The pump power is set to be 450mW and the input signal (at 1550nm) power is set to be -10 dBm per OAM mode (e.g. $HE_{6,1}^{even} + iHE_{6,1}^{odd}$). We chose the amplifier length (around 5m with small variations depending on the pump mode) at which the amplified signal power reaches its maximum. The erbium doping profile is assumed to be uniform within the annular guiding region with the doping concentration 1.5×10^{25} m^{-3}. Due to the circular symmetry of the air-core fiber, the simulated DMGs (denoted as ΔG in Fig. 2) using different pump modes (e.g. HE_{31} and EH_{11}) that belong to the same $OAM_{(L,\ m)}$ family (e.g. $OAM_{(2,\ 1)}$) are nearly identical. The calculated DMGs using the $TM_{0,m}$ and $TE_{0,m}$ modes resemble those using $OAM_{(1,m)}$ families. Similarly, the gains for different signal modes that belong to the same OAM family (e.g. $OAM_{5,1}^{\pm}$ and $OAM_{-5,1}^{\pm}$) are nearly identical. We summarize the 29 possible pump OAM families and their corresponding DMGs in Fig. 2. The physical origin of the DMG results from differences in the overlap of the pump modes, signal modes and the distribution of the rare earth dopant. The observed variation of DMGs for different pump modes is expected, as the pump modal intensity varies according to mode order. As shown by the pink highlighted region in Fig. 2, the best pump family that provides the lowest DMGs (~ 0.25 dB) is $OAM_{(8,1)}$. In comparison, the calculated DMG is about 3.1 dB when pumped by $OAM_{(0,1)}$, because the $OAM_{(0,1)}$ pump has a much better overlap with the $OAM_{(5,1)}$ signal mode over the $OAM_{(7,1)}$ signal mode. Although very low DMG can theoretically be achieved with the $OAM_{(8,1)}$ mode, in practice, the excitation of a pure $OAM_{(8,1)}$ pump is likely to be challenging. It is also possible that significant power will couple into other pump modes (for example, the adjacent mode families such as $OAM_{(4,2)}$ and $OAM_{(5,2)}$, which can induce large DMG) and compromise amplifier performance. This issue can be alleviated through further optimization of the erbium doping profile of the air-core EDF so that the DMG is more tolerant to a wider range of pump modes. However, due to space limitation, the discussion on doping profile optimization for core pumped air-core OAM EDF will be considered elsewhere.

(2) Cladding pumped operation

Cladding pumping has the advantages of very high pump powers (>10W) available from multimode pump diodes and a much reduced cost compared with the single mode pump diode in term of $/W. Initially, we assume the erbium doping profile to be the same ("flat top") as in the previous section. The inner cladding is assumed to be 70µm in diameter and the pump power is set to be 2.5 W, which creates a uniform pump intensity of 6.5×10^8 W/m^2 at the input end of the fiber. The input signal (at 1550nm) power is set to be -10 dBm per OAM mode (e.g. $\mathrm{HE}_{6,1}^{\mathrm{even}} \pm i\mathrm{HE}_{6,1}^{\mathrm{odd}}$). We chose the amplifier length at which the amplified signal power reaches its maximum (between 4.5-5.5m in this instance). The maximum simulated DMG (ΔG in Fig. 3b) is found to be 2.5 dB, which needs to be further minimized for practical applications. In order to do this, we introduce a design parameter a_1 that defines the dimension of the confined erbium doped layer inside the annular guiding region as shown in Fig. 3a. We explored the DMG dependence on the value of a_1, which varied from 3µm (i.e, uniformly doped core) to 5.75 µm. As shown in Fig. 3b, the DMG reduces to 0.25 dB as a_1 increases from 3 µm to 5.25 µm, and increases again when a_1 becomes larger than 5.25 µm. Finally, we simulated the WDM gain profiles of the cladding pumped OAM amplifier using the optimal a_1. 8 wavelength channels spaced equally from 1530nm to 1565nm and 12 OAM modes at each wavelength with the power of -20 dBm per mode per wavelength were used as the input signals. The fiber length was chosen to be 5m in order to balance the gain between short (i.e. 1530-1535nm) and long (i.e. 1550-1565nm) wavelengths. The WDM gain profiles for OAM modes |L|=5, 6, and 7 are shown in Fig. 3c. It can be seen that the gain curves for different spatial modes overlap with each other at all wavelengths within the C-band to within 0.25 dB illustrating excellent modal performance. The noise properties of the core- and cladding-pumped OAM-EDFA will be analyzed in future work.



(a) (b) (c)

Figure 3. (a) RIP of the air-core fiber with labelled design parameter a_1, (b) DMG as a function of a_1 and (c) the WDM performance of the cladding-pumped OAM amplifier.

4. Conclusions

We model the amplification of 12 OAM modes (|L|=5, 6 and 7) in an air-core EDF over the C-band. Under core pumping condition, we assessed the performance of all the supported pump modes (110 in total) individually and observed that the $\mathrm{OAM}_{(8,1)}$ pump mode provided the lowest DMG of 0.25 dB, whilst most of the other pump modes resulted in DMG >1 dB for signal modes $\mathrm{OAM}_{(5,1)}$ through $\mathrm{OAM}_{(7,1)}$. In practice, the clean excitation of pure $\mathrm{OAM}_{(8,1)}$ pump mode is likely to be challenging and expensive such that cladding-pumping is preferable. Using an optimal EDF design, DMGs of 0.25 dB and small signal gain of more than 20 dB can be achieved for the 12 OAM modes across the full C-band. In addition to OAM transmission, such an amplifier may find application to other communications modalities such as multicore fibers, where signals could be converted to orthogonal OAM modes, amplified, and then reconverted with minimal DMG and crosstalk.

5. References

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