

Analysis of Mode-Dependent Gain in Raman Amplified Few-Mode Fiber

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Abstract: We present a theory for Raman amplification in few-mode fibers based on the real (non LP) waveguide modes of the fiber. The condition for minimal mode-dependent gain is analyzed and reported for a few-mode fiber supporting 12 polarization- and spatial modes. The results are in agreement with recent experimental demonstrations.

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1. Introduction

Recent demonstrations of long-distance transmission over few-mode fiber (FMF) [1, 2] clearly show the potential of mode multiplexing to expand the capacity of a single optical fiber. However extending the benefits of optical amplification to mode-mixed systems has significant challenges. One notable advantage of mode multiplexing compared to space-division multiplexing using non-overlapping transmission paths [3] is the strong intensity overlap of the multiplexed channels, which enables sharing a single pump mode across multiple signal modes, in similarity to optical amplification in wavelength-division multiplexed (WDM) systems, where a single pump is shared across multiple WDM channels. Optical amplification in multimode fibers has been reported in [4], however no effort to minimize the mode dependent gain (MDG) had been undertaken. Minimizing the MDG for in-line amplification is important because of its direct impact on the achievable mode multiplexed capacity [5]. A scheme to reduce the MDG in a FMF based Erbium doped fiber amplifier (EDFA) has been proposed in [6] and experimentally investigated in [7], and Raman amplification in a FMF with low MDG has been reported in [1]. In this work we present a theory for distributed Raman amplification in FMF. In contrast to recent work on FMF-EDFAs [6], our work is based on the real waveguide modes (WGM) of the FMF (and not on the linearly polarized (LP) pseudomodes), which is particularly relevant for the case of distributed Raman amplification. The MDG dependence on the launch configuration of the Raman pumps are then investigated in detail for the case of a FMF supporting 12 polarization- and spatial modes (PSMs). The condition for minimum MDG are reported and compared with our recent experimental demonstration [1], confirming the validity of our approach.

2. Raman amplification in multi-mode fiber

In Raman amplification [8], the power of a pump laser at $\lambda_p = 1455$ nm is transferred to a signal wavelength at $\lambda_s = 1560$ nm. This process is phase insensitive but polarization dependent. The use of a depolarized pump allows to remove the polarization dependency of the gain. In a FMF both pump and signal power can be coupled into any mode supported by the fiber. The signal power S_m present in mode m at position z along the fiber is described by

$$\frac{dS_m}{dz} = -\alpha_S S_m + \gamma_R \left(\sum_n f_{n,m} (P_n^+ + P_n^-) \right) S_m, \quad \text{and} \quad (1)$$

$$\frac{dP_n^\pm}{dz} = \mp \alpha_P P_n^\pm \mp \frac{\lambda_S}{\lambda_P} \gamma_R \left(\sum_n f_{n,m} S_m \right) P_n^\pm, \quad (2)$$

where P_n^\pm is the power at the pump wavelength in mode n , P_n^+ and P_n^- denote co-propagating and counter-propagating pump, respectively, γ_R is related to the cross section of spontaneous Raman scattering, and α_S and α_P are the absorption coefficients at wavelengths λ_S and λ_P , respectively. The intensity overlap integrals are defined as

$$f_{n,m} = \frac{\int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} I_n(x,y) I_m(x,y) dx dy}{\int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} I_n(x,y) dx dy \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} I_m(x,y) dx dy}, \quad (3)$$

here we assume that the wavelength dependence of the mode profile $I_n(x,y)$ is negligible. Note that in general the superposition of different modes at the same wavelength will produce a spatial interference pattern commonly referred

to as speckle. The pattern can show a strong spatial intensity dependence, and Eqs. (1-2) are then only valid if the relative phase between the superimposed modes changes rapidly along propagation in the fiber, such as to justify fast power averaging (as seen by the signal) over the speckle patterns. This condition will be more easily met for counter-pumping than for co-pumping.

Eqs. (1-2) can be solved analytically in the undepleted pump approximation [8], the solution is given by

$$\frac{S_m(z)}{S_m(0)} = \exp(-\alpha_S z + A_m^+ (1 - e^{-\alpha_P z}) + A_m^- e^{-\alpha_P L} (e^{\alpha_P z} - 1)), \text{ where } A_m^+ = \frac{\gamma_R}{\alpha_P} \sum_n f_{n,m} P_n^+(0), \text{ and } A_m^- = \frac{\gamma_R}{\alpha_P} \sum_n f_{n,m} P_n^-(L), \quad (4)$$

where L is the length of the fiber and the coefficient A_m^\pm describe the mode-dependent exponential gain.

3. Real waveguide modes in a few-mode fiber

The FMF we use in our calculations is based on a step index (SI) profile with a core diameter of $d = 17 \mu\text{m}$, a refractive index of the cladding of $n_c = 1.46$, and a relative refractive index difference between core and cladding of $\Delta = 0.50\%$. The resulting calculated normalized frequency [9] is $V = 5$, at which the FMF supports the linear polarized LP_{01} , LP_{11} , LP_{21} , and LP_{02} pseudomodes. The LP pseudomodes are the solution of the mode equation under the weakly guided approximation [9], which offers the advantage that the spatial complex amplitude distribution and the polarization are decoupled; LP pseudomodes are therefore often used in mode-couplers and for theoretical calculations. However the real WGMs of the FMF [10], generally present solutions where both polarization and complex amplitude of the modes show a spatial dependence. This does not apply to the fundamental LP_{01} pseudomode, but applies to LP_{nm} pseudomodes for $n > 0$. The WGMs TE_{01} , TM_{01} , and HE_{21} forming the LP_{11} pseudomode are shown in Fig. 1 a).

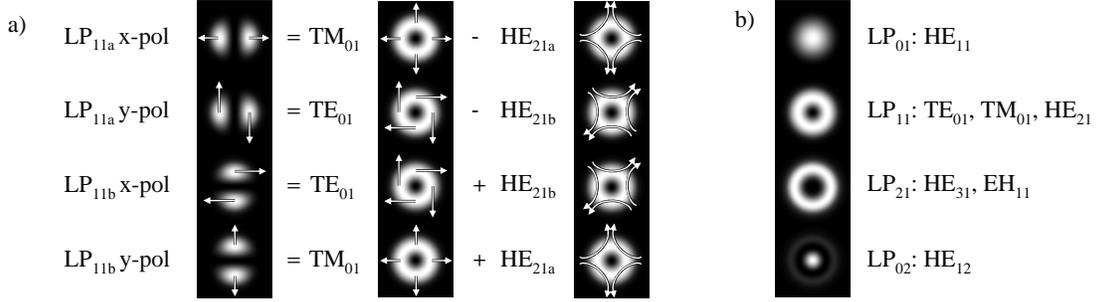


Fig. 1. a) Relation between LP_{11} pseudomode and real waveguide modes of the FMF, the arrows represent direction and sign of the electric field. b) Intensity profile of the real modes related to the LP pseudomodes.

The TE_{01} mode exhibits a tangential direction of the polarization, whereas the TM_{01} mode shows a radial polarization with respect to the center of the FMF. The WGMs TE_{01} , TM_{01} , and HE_{21} have different propagation constant β , which for our exemplary fiber results in a beat length of 0.31 m between TE_{01} and the twofold degenerated HE_{21} , 1.14 m between TM_{01} and HE_{21} , and 0.24 m between TE_{01} and TM_{01} , where TE_{01} has the largest and TM_{01} the smallest β , respectively. The consequence is that in a typical SI-FMF the LP “mode profiles” exist only every few cm’s or every few tens of cm’s, depending on the polarization, and are therefore not appropriate to describe the spatial intensity profiles in an optical fiber amplifier. Also note that the WGMs that form a particular LP pseudomode have the property that their intensity profile is almost identical. This can be seen in Fig. 1 a), which shows the ring shaped intensity profile of the TE_{01} , TM_{01} , and HE_{21} modes. Further, at any point in space the polarization of the TE_{01} is always perpendicular to the polarization of the TM_{01} mode, and the same applies also to the twofold degenerated HE_{21} mode. The intensity profiles of the waveguide modes related to LP_{01} , LP_{11} , LP_{21} , LP_{02} are shown in Fig. 1 b).

4. Gain equalization in few-mode fiber

In order to find the pump launch conditions that minimize the MDG for all the modes, the undepleted pump approximation is assumed and the amplification of the signals is then described by Eq. (4). The optimization is performed in two steps: First we ensured that all WGMs related to a particular LP pseudomode are equally amplified. This can be achieved by coupling the same amount of pump power in all respective WGMs. For the LP_{01} pseudomode this is achieved with a depolarized pump laser. For the LP_{11} pseudomode it is sufficient to excite one particular spatial LP_{11} pseudomode (for example LP_{11a}) with a depolarized pump laser. The first polarization will then excite an equal sum of TE_{01} and HE_{21a} modes, whereas the second polarization will generate TM_{01} and HE_{21b} modes (see also Fig. 1 a)).

Note that it is not absolutely necessary to excite all modes related to a particular LP pseudomode due to the short beat lengths between the modes and the gain averaging particularly for counter-pumping, as long as the pump intensity uniformly covers the LP₁₁ pseudomode intensity in a depolarized manner. For example, exciting a combination of only TE₀₁ and TM₀₁ modes should also produce homogeneous gain. Furthermore, coupling between the WGMs within an LP pseudomode due to fiber imperfections, fiber bending, or judiciously placed mode scramblers, may redistribute the power between the WGMs. Exciting all WGMs, however, should produce a more robust method for gain equalization.

As a second step towards the minimization of the MDG, the gain between WGMs belonging to different LP pseudomodes has to be equalized. This can be achieved by adjusting the pump powers coupled into the WGMs corresponding to a particular LP pseudomode. The intensity overlap integrals defined in Eq. (3) can be calculated for the intensity profile of the LP pseudomodes and are reported for a weakly guiding SI-FMF with $V = 5$ in Tab 1.

Table 1. Intensity overlap integral $f_{n,m}$ (in $10^9 / m^2$) for a FMF supporting 12 PSMs.

	LP ₀₁ : HE ₁₁	LP ₁₁ : TE ₀₁ , TM ₀₁ , HE ₂₁	LP ₂₁ : HE ₃₁ , EH ₁₁	LP ₀₂ : HE ₁₂
LP ₀₁ : HE ₁₁	6.24	4.12	2.85	4.62
LP ₁₁ : TE ₀₁ , TM ₀₁ , HE ₂₁	4.12	4.36	3.81	2.33
LP ₂₁ : HE ₃₁ , EH ₁₁	2.85	3.81	3.88	2.12
LP ₀₂ : HE ₁₂	4.62	2.33	2.12	6.15

The MDG can now be minimized by varying the pump power configurations $P_n^+(0)$ and $P_n^-(L)$ and finding the minimum value for the error function ($\max(A_m^\pm) - \min(A_m^\pm)$), evaluated over all modes m of interest. In order to minimize the MDG along the whole fiber, the configurations for forward- and backward amplification, have to be optimized individually. However the resulting optimum configuration will be the same for both directions.

The optimum configuration for 6, 10, and 12 PSMs in a SI-FMF is the following: For 6 PSMs (LP₀₁ and LP₁₁) the optimal pump power configuration with perfectly equalized gain is obtained when 10% of pump power is coupled into LP₀₁ and 90% into the WGMs constituting LP₁₁; this is close to the experimental condition explored in [1], where equalized gain in a depressed cladding FMF was observed by coupling 100% into the WGMs constituting LP₁₁. For 10 PSMs (LP₀₁, LP₁₁, and LP₂₁) the optimum launch condition is found to be 77% of pump power coupled into LP₁₁ and 23% into the WGMs related to LP₂₁, leading to a residual MDG of 1 dB for each 10 dB of Raman gain. For 12 PSMs (LP₀₁, LP₁₁, LP₂₁, and LP₀₂ pseudomodes) the residual MDG can be reduced to 0.13 dB for each 10 dB of Raman gain when 69.6% of pump power is launched into the WGMs constituting LP₂₁ and 30.4% into the WGMs constituting LP₀₂. Note that no power is launched into LP₀₁ and LP₁₁ in this case.

Because of the strong intensity overlap between the modes, the pump power is effectively shared between the signal modes, and produce a significant power advantage [11]. In order to quantify this advantage we compare the total pump power required to amplify $n/2$ SMFs with the same effective area as the LP₀₁ pseudomode of the SI-FMF, where n is the number PSMs used of the FMF. The equivalent multiple SMF system requires 2.1, 2.8, and 3.2 times the total Raman pump power of the SI-FMF system when 6, 10, or 12 PSMs are used, respectively. This represents a considerable power advantage which will however diminish with pump depletion.

In conclusion we have presented a theory for Raman amplification in few-mode fiber based on the real waveguide modes. We showed how to minimize the mode dependent gain by choosing optimizing the modal pump power distribution. For a step index few-mode fiber supporting 12 spatial- and polarization modes, we predict a residual mode dependent gain of 0.13 dB for each 10 dB of Raman gain using our method.

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