Gain Inhomogeneity in L-band Phosphosilicate-based Erbium-Doped Fiber Amplifiers

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Abstract: We report large pump-mediated inhomogeneity in an L-band phosphosilicate-based EDFA, pumped in the 1480 nm absorption band. We have investigated inhomogeneous effects as a function of average inversion level, input signal power, and pumping configuration.

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Introduction

The inhomogeneous behaviour of an Erbium-Doped Fiber Amplifier (EDFA) results from the Stark splitting levels associated with the \(^4I_{13/2}\) and \(^4I_{15/2}\) states being slightly different at different erbium sites within the glass host. It can have many adverse effects on the performance of the EDFA. For example, inhomogeneous gain saturation near the spectral region of a strong signal, also known as spectral hole burning, can cause havoc to amplifier gain control and degrade the transient performance of a wavelength-division-multiplexed network during a wavelength add/drop event [1-3]. Another manifestation of the erbium inhomogeneity is the pump-mediated inhomogeneous (PMI) effect, which refers to the non-homogeneous spectral gain deviation as a result of a small variation in pump wavelength.

For long-haul optical systems or large optical networks that employ many EDFAs, PMI effects should be strictly controlled in order to meet the tight tolerance on EDFA gain deviation. It has been shown that PMI effects are very large (2-3 dB of gain deviation) for C-band EDFAs [4-6], but previous studies on L-band EDFAs have seen little PMI effect (not distinguishable from measurement uncertainty), whether the EDFA was pumped in the 980 nm or the 1480 nm absorption band [7]. However, these studies were carried out on EDFAs made with germanosilicate or aluminosilicate erbium-doped fibers. Research has shown that modifying the erbium host material systems can further extend the L-band amplification bandwidth [8-10], and in particular, phosphosilicate-based erbium fiber has been successfully deployed in a 50 nm gain-flattened EDFA with full functionality operating in the extended L-band [11]. But a study of PMI effects in phosphosilicate-based erbium fiber has not been previously reported.

In this paper, we report the first observation of large PMI effects in an L-band phosphosilicate-based EDFA pumped in the 1480 nm absorption band. We have systematically investigated the PMI effect on phosphosilicate EDF gain spectrum as a function of average inversion, input signal power and pump configuration.

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Experimental Results and Discussion

A single-coil amplifier operating at room temperature was used for this investigation. The active coil was a 20-m long phosphosilicate fiber doped with Er<sup>3+</sup> at a concentration of 3700 ppm, fusion spliced to SMF28™ pigtails with splice loss ≤0.1dB at each end. Wavelength combiners (1480/1550 type) were placed both at the input and output of the coil to allow forward, backward, or bi-directional pumping. Narrow-band lasers of approximately equal power and uniformly covering the extended L-band (1568 to 1616 nm) at 100 GHz spacing were multiplexed and fed to the input of the EDFA. Gain was measured by taking the signal spectra at the input and output of the amplifier via an optical spectrum analyzer, and therefore includes the input- and output-stage component losses, which are constant for all the measurements. Two pairs of grating-stabilized pumps were used: the first pair at 1465 nm, and the second pair at 1487 nm. The wavelength variations for all pumps were within ±0.5nm over their operating range. Pump power at the entrance of the erbium coil as a function of drive current was characterized for each pump.

| Table 1 EDFA Gain Measurement Conditions |
|-----------------|-----------------|-----------------|
| \( \lambda_p = 1465 \text{ nm} \) | \( \lambda_p = 1487 \text{ nm} \) |
| Forward pumping, average inversion 0.32 | \( P_{in} = 2 \text{dBm, 5dBm, 10dBm} \) | \( P_{in} = 2 \text{dBm, 5dBm, 10dBm} \) |
| Forward pumping, average inversion 0.43 | \( P_{in} = 2 \text{dBm, 5dBm, 10dBm} \) | \( P_{in} = 2 \text{dBm, 5dBm, 10dBm} \) |
| Forward pumping, average inversion 0.46 | \( P_{in} = 2 \text{dBm, 5dBm, 10dBm} \) | \( P_{in} = 2 \text{dBm, 5dBm} \) |
| Bi-directional pumping, average inversion 0.49 | \( P_{in} = 2 \text{dBm, 5dBm, 10dBm} \) | \( P_{in} = 2 \text{dBm, 5dBm} \) |
| Bi-directional pumping, average inversion 0.53 | \( P_{in} = 2 \text{dBm, 5dBm, 10dBm} \) | \( P_{in} = 2 \text{dBm, 5dBm} \) |

The gain spectrum was measured at three different input powers and five different average inversion levels, as given in Table 1. The five inversion levels (estimated values given in Table 1) cover the typical operating range of erbium coil average inversion in an EDFA. Note that, for a multi-coil EDFA, the average inversion of the individual coils can be quite different from each other, and therefore our investigation covers a large range of average inversions. For each inversion level, the condition where \( P_{in} = 2 \text{dBm} \) and \( \lambda_p = 1465 \text{ nm} \) was used as a reference, and for all other conditions in the same row as the reference in Table 1, the pump powers were adjusted so that the gain shape has the best match to the reference gain shape. This was to ensure that any dynamic gain tilt was minimized, and the average inversion level was kept to be as close to the reference level as possible. When bi-directional pumping was used, in order to ensure the same pump distribution was used for 1465 and 1487 nm pumping, the forward and backward pump powers were set to be equal.

![Figure 1](image-url)  
Figure 1. Comparison of gain spectra under 1465nm and 1487nm pumping at \( P_{in} = 2 \text{dBm} \). (a) Forward pumping at average inversion of 0.32; (b) Forward pumping at average inversion of 0.43; (c) Bi-directional pumping at average inversion of 0.49. (d) Gain difference between 1465nm and 1487nm pumping for different inversion levels (indicated in parentheses) and pumping configuration.
As seen from Figure 1, significant PMI effects, which resulted in a peak-to-peak gain variation as much as 1.2 dB, were observed in the extended L-band. These PMI effects are qualitatively similar to those reported for C-band in germanosilicate or aluminosilicate EDFAs [4-5]. Moreover, by comparing the spectral gain deviation obtained between 1465 and 1487 nm pumping for various inversion levels and pump configurations (Figure 1d), we can clearly see that the PMI effect are much more affected by pump configuration than by the change in average inversion level. The significant difference made by pump configuration can be qualitatively explained as follows: in a forward pumping configuration, the pump first generates C-band ASE, and then the ASE amplifies the L-band signal as they propagate together along the fiber; while in a bi-directional pumping configuration, the L-band signals are directly amplified by the pump near the output of the erbium coil, and hence a more significant PMI effect. Our observations at other input power levels (5 dBm and 10 dBm) are consistent with those made at 2 dBm input level.

The pump wavelength difference used here is 22 nm, which is generally considered large compared to the typical wavelength variation found among a batch of pumps. However the central wavelength of a typical 14xx nm pump without grating stabilization can drift as much as 20 nm over the operating range of drive current. Consequently, when an EDFA is operating under different power conditions, considerable gain deviation can result from pump wavelength drift. Therefore, low-ripple amplifier designs, especially those operating in the 1568 – 1620 nm range, would benefit from wavelength-stabilization of the pump lasers, for example, by means of a fiber grating.

![Figure 2](image_url)

Figure 2 Inhomogeneous gain deviation observed for different input levels (2dBm, 5dBm and 10dBm) under fixed \( \lambda_p = 1465 \) nm. (a) forward pumping, at average inversion of 0.43. (b) bi-directional pumping at medium average inversion of 0.49. (c) bi-directional pumping at high average inversion of 0.53.

![Figure 3](image_url)

Figure 3. Inhomogeneous gain deviation between forward and bi-directional pumping, observed for input power of 2, 5, and 10 dBm. Pump wavelength was fixed at 1487nm, average inversion for all cases was held at ~0.49.

Since gain inhomogeneity originates from the fact that \( \text{Er}^{2+} \) ions occupy slightly different sites in the glass matrix and therefore have different spectral broadening as well as slightly different Stark split levels, we should expect inhomogeneous behaviour even without pump wavelength variation. If different portions of these inhomogeneous sites were excited due to different power levels or different
pumping configurations, inhomogeneous gain deviation would result, even when average inversion is kept constant. It is important for EDFA designers to learn the magnitude of such inhomogeneous effects under different excitation conditions. We therefore measured the inhomogeneous gain deviation with fixed pump wavelength. As seen in Figure 2, the inhomogeneous effects observed for the different input levels are small but noticeable (peak to peak ~0.2 – 0.4dB). The inhomogeneous effect also tends to be larger for wavelength region below 1580 nm, which, as expected, coincides with the region where gain slope is the steepest. Even for the same input level, we observed inhomogeneous gain deviation between forward pumping and bi-directional pumping configuration (Figure 3), but its magnitude is also relatively small (0.3 dB peak-to-peak).

Conclusion

We have investigated the various manifestations of erbium gain inhomogeneity in an L-band phosphosilicate-based EDFA. We have observed large pump-mediated inhomogeneous gain deviation in the extended L-band (1568 to 1616 nm) when the EDFA was pumped in the 1480 nm absorption band. This behaviour is distinctly different from L-band germanosilicate- or aluminosilicate-based EDFAs, and is qualitatively similar to those reported for C-band conventional EDFAs. The PMI effect was much more pronounced for bi-directional pumping configurations. Although pump wavelength variation has the largest effect on spectral gain deviation, small inhomogeneities were also observed for different input power levels and different pumping configurations under a fixed pumping wavelength.

References
