

Characterization of Gain Spectral Variation of Erbium-doped Fibers Codoped with Aluminum

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ABSTRACT

Characteristics of gain spectral variation of EDFs and its dependence on aluminum doping level and fiber mode design are quantitatively studied. Based on experimental data and manufactured fibers with different aluminum levels, the correlation between aluminum concentration and both absorption spectrum and gain flatness is revealed. Gain spectral variation for over a million meters of EDFs manufactured in last several years is presented. The result shows that peak-to-peak spectral shape variation for all these fibers are within 0.8% in a 36nm C-band window.

Keywords: erbium-doped fiber, gain spectrum, optical communication, EDFA, aluminum

1. INTRODUCTION

Erbium-doped fiber amplifiers (EDFA) have been widely used in optical communication systems, such as long-haul transport systems and CATV applications⁽¹⁾. Innovative design and optimization of erbium-doped fibers (EDF) have played a critical role in these applications as they enable efficient and low-noise amplification of light. Precise gain spectral shape control of EDF is essential for modern high performance EDFAs in WDM applications. Aluminum, a key EDF codopant, has a strong effect on both the absorption and stimulated emission spectra in addition to other beneficial effects of reducing the erbium ion clustering, improving solubility, and controlling erbium radial doping profile^{(2), (3)}.

The paper reveals quantitative characteristics of gain spectral variation with different aluminum concentrations. Other effects that contribute to the spectral variation are also discussed. First, the characterization method of the EDF's spectral properties is firstly introduced. Then, absorption and gain spectral shape data with different aluminum levels based on experimental data are studied. Finally, spectral shape variation data of over millions of meters EDFs manufactured in Lucent/OFS in last several years using modified chemical vapor deposition (MCVD) process is presented. The result shows that by properly controlling the aluminum doping level and fiber cutoff in the EDF manufacturing process, the gain spectral shape can be consistently maintained both along the fiber draw position and for different performs.

2. GAIN SPECTRUM CHARACTERIZATION

Two types of measurement techniques are widely used to determine the spectral properties of erbium-doped fibers^{(5), (6), (7)}. The first technique directly measures fundamental properties of the erbium ions -- absorption and emission cross-sections. This measurement requires known knowledge of erbium ion distribution and concentration as well as modal properties of the fiber. The second method described by Giles et. al.⁽⁷⁾ measures two wavelength-dependent fiber coefficients $\alpha(\lambda)$, absorption per unit length when all erbium ions in the ground state, and $g^*(\lambda)$, small signal gain per unit length when all erbium ions in the metastable upper state, by assuming radially symmetric optical mode and dopant distribution. $\alpha(\lambda)$ and $g^*(\lambda)$ are determined by absorption and emission cross-sections, overlap factor, and erbium concentration. Absorption $\alpha(\lambda)$ and gain $g^*(\lambda)$ are defined by

$$\begin{aligned}\alpha(\lambda) &= \sigma_a(\lambda)\Gamma(\lambda)N_0 \\ g^*(\lambda) &= \sigma_e(\lambda)\Gamma(\lambda)N_0\end{aligned}\tag{1}$$

where $\sigma_a(\lambda)$ and $\sigma_e(\lambda)$ are radially averaged absorption and emission cross sections of erbium ions, N_0 is the averaged erbium ion concentration, and $\Gamma(\lambda)$ is the overlap factor between the optical mode field and erbium ions, which can be determined from optical mode field and erbium ion distribution.

$$\Gamma(\lambda) = \int_0^{2\pi} \int_0^{+\infty} \psi(r, \phi) n_0(r, \phi) r dr d\phi \quad (2)$$

where $\psi(r, \phi)$ is the normalized mode intensity distribution of the fundamental mode and $n_0(r, \phi)$ is the normalized erbium ion density.

For a simplified fiber design with a step core index profile and a core radius of a , the normalized mode intensity field is ⁽⁸⁾

$$\psi(r) = \begin{cases} \frac{1}{\pi} \left[\frac{Y}{aV} \frac{J_0(r/a \cdot X)}{J_1(X)} \right] & \text{for } r < a \\ \frac{1}{\pi} \left[\frac{X}{aV} \frac{K_0(r/a \cdot Y)}{K_1(Y)} \right] & \text{for } r \geq a \end{cases} \quad (3)$$

where the fiber V parameter is $2\pi a NA / \lambda$. $J_{0,1}$ and $K_{0,1}$ are Bessel and modified Bessel functions, respectively. Parameters X and Y are determined by the characteristics equation that satisfies the boundary conditions at $r = a$, and $V^2 = X^2 + Y^2$.

Assuming a homogeneously broadened gain medium, we can then predict the gain spectral shape using average inversion method ⁽³⁾ from the measured EDF absorption and small signal gain by neglecting small effect from the background loss. For a length of EDF L with a given average inversion level Inv , the gain spectral shape or gain spectrum can be calculated by

$$G(\lambda, Inv) = [g^*(\lambda) \cdot Inv - (1 - Inv)\alpha(\lambda)]L \quad (4)$$

In reality, Inhomogeneous characteristics such as pump wavelength dependence and spectral hole burning (SHB) also contributes to spectral shape variation. Practically, the homogeneous assumption used for commuting the gain spectrum is sufficient to compare the gain spectral shape difference for different EDFs.

3. RESULTS AND DISCUSSION

It is apparent from equations (1) and (4) that the spectral properties of EDFs are determined by absorption and emission cross-sections and the overlap factor, both of which are wavelength dependent. For simplicity, the effect is concentration is neglected. Spectral characteristics of both absorption and emission cross-sections depends on the host glass and dopant composition. In aluminum codoped EDFs, it is known that aluminum concentration drastically alters the absorption and gain spectra, thus the amplifier's gain spectral shape. In addition, the overlap factor $\Gamma(\lambda)$ is also wavelength dependent because the mode field size varies with wavelength.

3.1. Role of aluminum concentration

To quantitatively determine the relationship between aluminum concentration and spectral properties of EDFs, it is useful to use measurable process parameters that indicate the aluminum concentration. It has been shown that EDFs with higher aluminum levels have a higher shoulder at 1480nm. Therefore, the ratio of absorption of 1480nm relative to the absorption peak, called "Al ratio" or R_{al} , can be used differentiate different aluminum doping levels ⁽⁴⁾. Normalized

absorption spectra of fibers with three different aluminum concentrations are shown in Fig. 1. Cutoffs of these fibers are all around 900nm. The Al ratios for these three fibers are 0.3758, 0.4343, and 0.4590, respectively. The higher value of Al ratio represents higher aluminum doping concentration.

From Fig. 1, it is also apparent that with the increase of the aluminum level, the wavelength of the absorption peak shifts to a shorter wavelength. To quantitatively study the effect of aluminum doping levels on the absorption spectral shape, a series of fibers with different aluminum concentrations have been made. The value of R_{al} of these fibers varies from 0.31 to 0.47. The absorption peak wavelength vs. Al ratio - R_{al} for different fibers is shown in Fig. 2. It appears that the absorption peak wavelength varies linearly with Al ratio when R_{al} value is less than 0.44. The peak wavelength decreases asymptotically with further increase of aluminum concentration. Higher aluminum concentration beyond R_{al} of 0.44 only has minimum effect of broadening the spectral bandwidth.

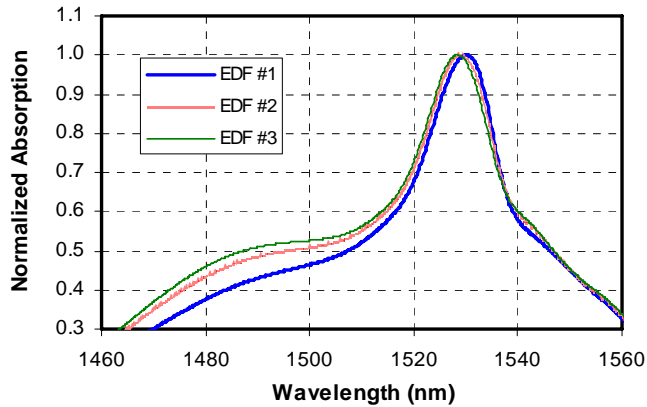


Fig. 1 Normalized absorption spectra

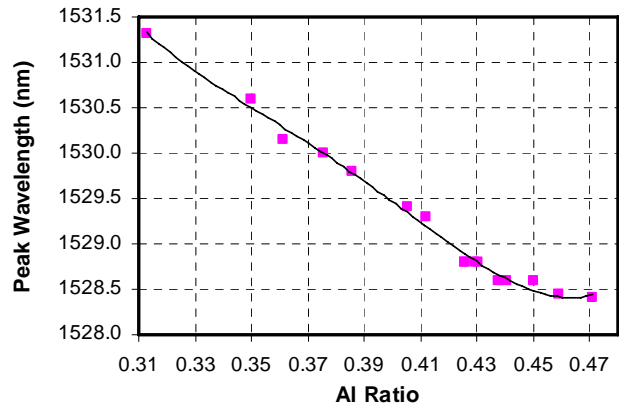


Fig. 2 Absp peak wavelength vs. Al ratio

To exam the gain spectral shape characteristics of the fibers with different aluminum concentrations, gain spectra of above mentioned three fibers are calculated using equation (4). The bandwidth of the spectra is 36nm from 1529nm to 1565nm and the flatness is optimized by selecting proper average inversion level. An appropriate fiber length is chosen to achieve a minimum 20dB gain in each case. Gain spectra of these fibers are shown in Fig. 3 Results confirm that higher aluminum concentration not only broadens the spectral bandwidth by shifting the 1532nm peak to a shorter wavelength but also reduces the gain peak at around 1532nm and thus improves the overall gain spectral flatness. In addition, higher aluminum level improves the flatness in the 1540nm to 1560nm window.

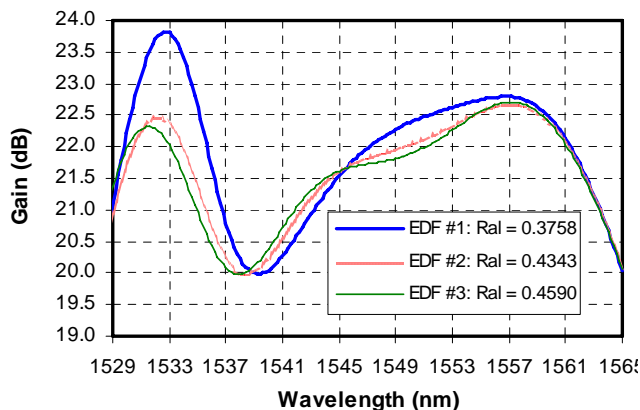


Fig. 3 Gain spectra of different EDFs in 36nm bandwidth

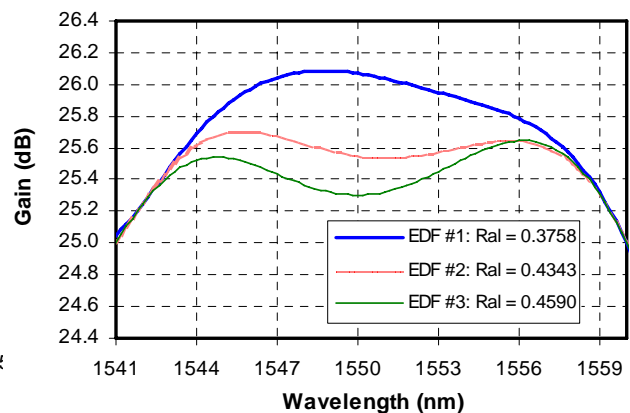


Fig. 4 Gain spectra of different EDFs in 19nm bandwidth

To closely exam the gain spectral shape characteristics of same three EDFs in a 19nm bandwidth from 1541nm to 1560nm, we optimize these gain spectra by selecting proper inversion level and fiber length to achieve a flat gain shape and a minimum 25dB gain. These gain spectra are shown in Fig. 4. It is evident that higher aluminum concentration improves the spectral flatness in the 19nm bandwidth. In addition, higher Al level creates a spectral dip at around 1550nm. This can possibly be used as an accurate indicator of aluminum doping level.

To quantify the relationship between the flatness and aluminum concentration in 19nm bandwidth, we calculated the gain flatness for manufactured fibers with different Al ratios. As shown in Fig. 5, the result indicates that flatness improves almost linearly with the increase of the Al ratio up to 0.44, beyond which the flatness seems to approach 0.6dB asymptotically. Consistent with previous result of peak absorption wavelength for different aluminum levels, R_{Al} value of 0.44 seems to be a transition threshold.

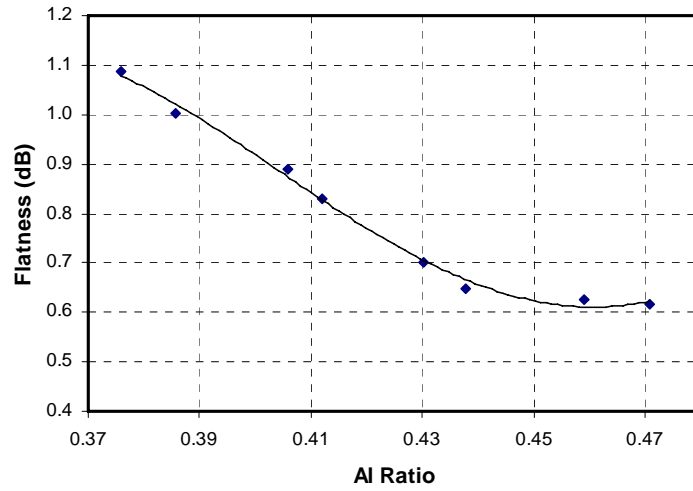


Fig. 4 Spectral flatness in 19nm bandwidth with 25dB minimum gain vs. Al ratio

3.2. Overlap factor

The overlap factor determined by equation (2) depends on the overlap between optical mode field and erbium ions. The erbium ions are typically confined to the central portion of the mode. The optical mode field varies with wavelength. Shorter wavelength has a slightly smaller mode field, thus a larger overlap factor value. Since the “Al ratio” is the 1480nm absorption normalized to the peak absorption around 1530nm, this ratio varies with the fiber cutoff. Shorter cutoff fibers produce a higher ratio than longer cutoff fibers. The ratio of the overlap factors reaches 1 when the cutoff approaches infinity.

3.3 Spectral shape consistency

Gain spectral shape consistency is critical for both amplifier performance and cost saving in optical amplification for WDM applications. Based on the discussion above, we know that accurate control of both aluminum delivery and fiber cutoff in fiber manufacturing process are the key to produce EDFs with consistent gain spectra. To quantify the gain shape variation, we have analyzed the gain spectral data of over one million meters of MP980 EDFs with a total of 14 preforms made in Lucent/OFS in the last several years. The MP980 EDF was designed for medium power amplification. Typical peak absorption, NA, and cutoff of MP980 are 6dB/m, 0.23, and 900nm, respectively. Aluminum concentration is typically around 12 M%.

First, we studied the gain spectral variation along one of MP980 preforms. Both $\alpha(\lambda)$ and $g^*(\lambda)$ at five randomly selected draw positions along the perform were accurately measured. Fiber draw positions are at about 25km, 55km,

65km, 70km, and 80km, respectively. High measurement repeatability has to be maintain to assure the integrity of the results. The gain spectra were then calculated from the measured $\alpha(\lambda)$ and $g^*(\lambda)$ using average inversion method. Proper average inversion level and fiber length were used to optimize the flatness and to reach the required gain. We studied both 36nm bandwidth and 19nm cases in C-band.

The result of spectral shape variation in 36nm bandwidth from 1529nm to 1565nm with a minimum 20dB gain is shown in Figs. 5 and 6, respectively. The spectral shape deviation in Fig.5 is gain difference between the each gain spectrum at the designated draw position and the average of five gain spectra. Fig. 6 shows the calculated maximum shape deviation at each fiber draw position. The maximum shape deviation is less than 0.05dB for all five draw positions. Similar results in 19nm bandwidth from 1541nm to 1560nm with a minimum 25dB gain are shown in Figs. 7 and 8. In this case, the maximum shape deviation is less than 0.02dB.

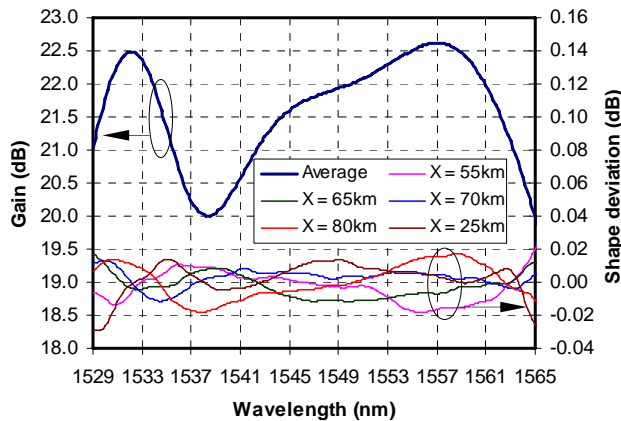


Fig. 5 Gain spectral shape deviation along a preform (36nm)

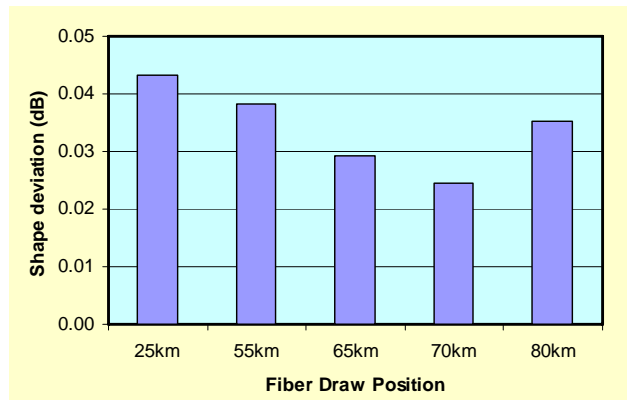


Fig. 6 Maximum shape deviation along a preform (36nm)

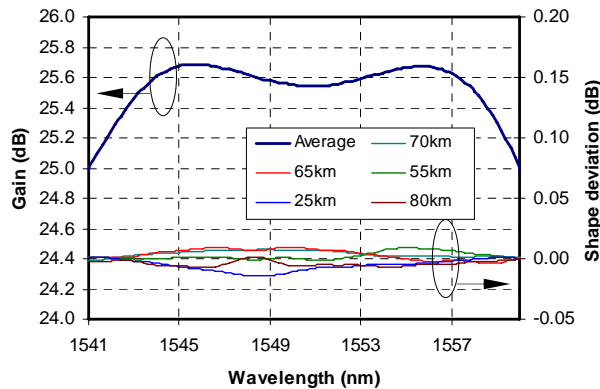


Fig. 7 Gain spectral shape deviation along a preform (19nm)

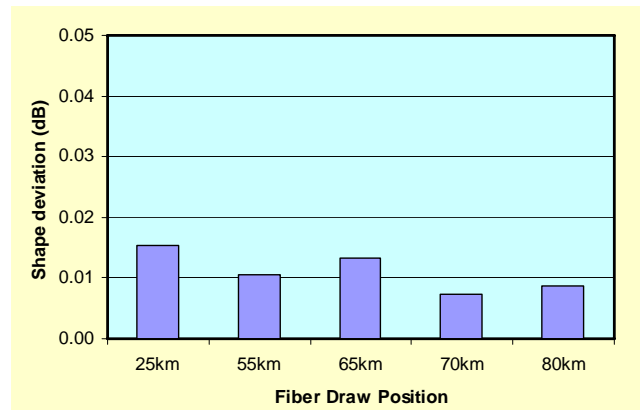


Fig. 8 Maximum shape deviation along a preform (19nm)

Then, we investigated the gain spectral variation over one million meters of MP980 EDFs from 14 different fiber preforms manufactured in last several years in our Somerset facility to have a broader and overall picture of our EDF manufacturing process,. For each preform, one measurement position was randomly selected. Rigorously speaking, more measurement data are required to yield a good statistics. Practically, as the shape deviation along the preform is small, one measurement for each preform should still be sufficient to generate reasonably good statistical data.

Similar to the approach used above, we measured both $\alpha(\lambda)$ and $g^*(\lambda)$ for each preform and then calculated the gain spectra with an optimized flatness in 36nm bandwidth and a minimum 25dB gain. As shown in Figs. 9 and 10, results indicate that the spectral shape variation for over one million meters of EDFs ranges from 0.05dB to 0.19dB, or 0.2% to

0.76%. So, the maximum shape deviation is less than 0.2dB at a 25dB gain, or 0.8%. It is believed that the main contribution to the shape deviation is due to different aluminum concentration levels. Al ratios for preforms #7, #10, and #13 are 0.4309, 0.4343, and 0.4378, respectively. Better gain shape consistency can be possibly achieved by closely controlling the aluminum concentration, or simply by matching preforms with similar Al ratio.

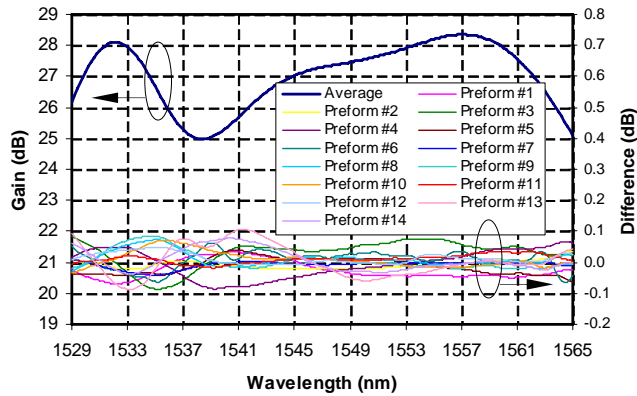


Fig. 9 Gain spectral shape deviation for 14 MP980 preforms

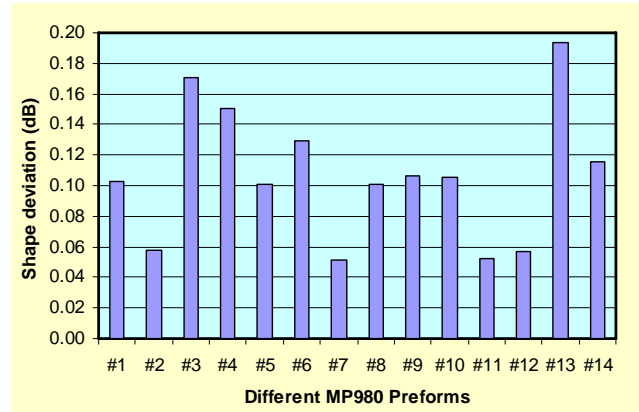


Fig. 10 Maximum shape deviation (36nm)

4. CONCLUSIONS

Gain spectral properties of EDFs with different aluminum doping levels have been quantitatively studied. Results show that Al ratio, an indicator of aluminum concentration, has a linear correlation with the peak absorption wavelength up to Al ratio of 0.44, beyond which the bandwidth improvement due to higher aluminum level is minimum. Similar conclusion can be drawn from the investigation of gain flatness characteristics in 19nm spectral bandwidth for different aluminum concentrations. From the spectral bandwidth and flatness standpoint, this ratio seems to be a transition threshold, which provides a good guideline of aluminum doping level.

Consistent gain spectral shape can be properly maintained by tightly controlling the aluminum concentration level and fiber cutoff. Statistical results show that spectral shape variation along a MP980 preform in 36nm bandwidth with minimum 20dB gain and 19nm bandwidth with 25dB minimum gain are less than 0.05dB and 0.02dB, respectively. Further study of over one million meters of fibers from 14 MP980 EDF preforms indicates that the spectral shape variation ranges from 0.05dB to 0.2dB with minimum 25dB gain. Therefore, the overall peak-to-peak spectral shape consistency over one million meters of EDFs is better than 0.8%.

5. REFERENCES

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