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Novel Erbium Doped Fiber for High Power Applications

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A novel erbium doped fiber (EDF) designed for high power WDM applications is presented. The fiber design and performance versus numerical aperture and cutoff wavelength are described based on an advanced EDFA simulation model. The optical and spectral characteristics of the high power fiber are shown. Experimental measurement results of this fiber and comparison with typical commercially available EDFs are given. Performance results show that the new EDF is ideal for high power EDFA applications. It features high power conversion efficiency at high pump power, especially with 980nm pumping, extremely flat gain shape, very low splice loss to typical pigtail fibers, and negligible macro-bending loss.

Keywords: erbium-doped fiber, high power, gain spectrum, aluminum, splice loss, macro-bending loss

INTRODUCTION

Erbium-doped fiber amplifier (EDFA) continues to be widely used in optical communication, such as long-haul transport systems and CATV applications (1) because of its high performance and cost-effectiveness. Innovative design and optimization of erbium-doped fibers (EDF) have played a critical role in these applications. Design of confined mode field and erbium distribution enables efficient and low-noise amplification of light at low and medium power range (2). For high power applications, large mode area fiber with low NA lowers pump intensity, thus reduces nonlinear effects, such as 980nm pump excited state absorption which limits the power conversion efficiency at high power (3). High performance EDFAs for high power WDM applications require EDF with both large mode area and flat gain spectral shape. Commercially available low NA fiber, e.g. HP980 of OFS, is not suitable for WDM application because of its poor spectral flatness.

We report a novel erbium doped fiber design, which offers not only large mode area with low NA to reduce nonlinear effect, but also high aluminum content to improve gain spectral flatness. In this paper, we firstly illustrate the design aspect of this high power EDF using an available advanced EDFA simulation method. The effect of fiber numerical aperture and cutoff wavelength is discussed using power conversion efficiency as a figure of merit. Then we discuss the design and characteristics of the new high power EDF, as well as its spectral shape comparison with other commercially available fibers. Finally, we present some experimental results to show the performance of this fiber for high power applications.

HIGH POWER ERBIUM DOPED FIBER

It is well known that erbium-doped fiber design needs to be optimized for different amplifier applications. Regardless of applications, high performance EDF for WDM applications should possess some fundamental characteristics: high power conversion efficiency at required pump level, flat spectral gain shape, low macro-bending loss, and low splice loss to typical pigtail fibers. Good EDF design is critical for achieving these demanding performance requirements. In this section, we firstly review the EDFA simulation model briefly. Then, we discuss the design of erbium-doped fiber for high power applications. Finally, we describe the optical and spectral characteristics of the high power EDF, its performance, and comparison with other commercially available EDFs .

2.1. Simulation Model

An optimal EDF for high power applications requires both fiber waveguide design and doping composition design. Fiber waveguide parameters, such as numerical aperture (NA), cutoff wavelength, and erbium dopant confinement, determine the overlap between optical mode field and erbium ions, thus the fiber performance. The design of high NA and confined erbium ions is more beneficial for low power applications. For high power applications pumped at 980nm, it is known that excited state absorption (ESA) from the $^4I_{11/2}$ significantly affects the efficiency of EDFAs. Lower NA reduces this non-linear effect. However, for optimal fiber performance, an appropriate design is essential On the other hand, doping composition design, which mostly defines EDF's spectral shape characteristics and erbium ion clustering effect, is also critical.

In order to quantitatively reveal the high power EDF design, an EDFA model based on work by Giles et. al. (4) is used to find the effect of fiber waveguide parameters on the amplifier performance in the high power region. Additional loss mechanisms, such as erbium ion clustering effect and pump ESA at 980nm, are also included in the model (6), (7), (8). This EDFA model assumes radially symmetric optical mode and dopant distribution, and that erbium radial distribution is well approximated by an overlap factor. Measured Giles parameters, $\alpha(\lambda)$ – absorption per unit length and $g^*(\lambda)$ – small signal gain per unit length, are used basic modeling parameters. Giles parameters can be related to absorption and emission cross-sections, overlap factor, and erbium concentration by following overlap integral.

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

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 via the following equation.

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

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. If we assume that the fiber has a step core index core with a radius of "a", the radially symmetric mode intensity field then is (8)

$$\psi(r) = \begin{cases} \dfrac{1}{\pi}\left[\dfrac{Y}{aV}\cdot\dfrac{J_0(r/a\cdot X)}{J_1(X)}\right]^2 & for \quad r < a \\ \dfrac{1}{\pi}\left[\dfrac{X}{aV}\cdot\dfrac{K_0(r/a\cdot Y)}{K_1(Y)}\right]^2 & for \quad r \geq a \end{cases} \tag{3}$$

where V equals $2\pi a NA/\lambda$. $J_{0,1}$ 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 fiber core/cladding interface..

The loss mechanism, pump ESA at 980nm, is modeled by adding an additional upper level for the pump ESA with population n_3 and introducing pump excited state absorption $\alpha_{pump}^{ESA}(\lambda)$ to the pump power propagation equation. The erbium clustering effect due to different erbium concentrations and the NA-dependent background loss are also included in the model. The modeling parameters or coefficients are determined from literature and experiments.

2.2 High Power EDF Design

Based on the model and assumptions mentioned in the preceding section, we can determine EDF performance versus fiber parameters, such as numerical aperture and LP_{01} cutoff wavelength. In the simulation, the modeling parameters based on the fiber design are firstly determined. Then the power conversion efficiency, a figure of merit, is calculated at different pump power levels. The power conversion efficiency (PCE) is defined as

$$PCE = \frac{P_{out}^{s} - P_{in}^{s}}{P_{in}^{p}} \tag{4}$$

where P_{in}^{s} is the input signal power, P_{out}^{s} is the output signal power, and P_{in}^{p} is pump power injected into the EDF.

Figure 1 shows the modeling result of PCE versus launched 980nm pump power. In the simulation, the erbium distribution is assumed to be flat-top and has same radius of fiber core. The fiber is assumed to have a step index core. We only vary numerical aperture of the fiber. The corresponding background loss change due to different NAs is included. All other fiber parameters are kept the same. The input signal power is 0dBm at 1550nm wavelength and 980nm pump co-propagates with signal. At each pump power level, fiber length is optimized to achieve maximum output signal power.

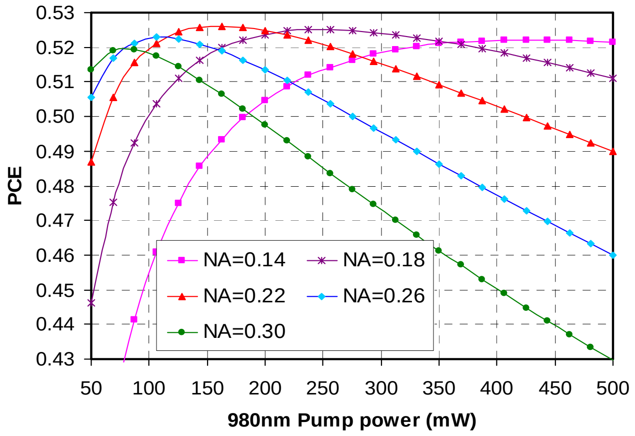

Fig. 1 PCE vs. pump power for different fiber NAs

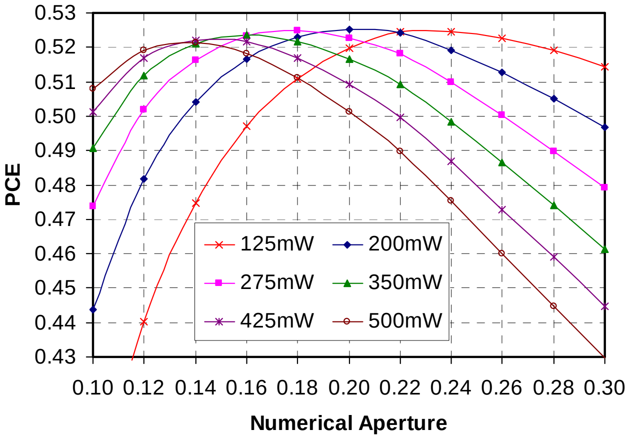

Fig. 2 PCE vs. NA

The simulation result shows that EDF performance strongly depends on fiber numerical aperture. Low NA fiber is beneficial for high power applications, whereas high NA fiber is more suitable for low power applications as we already know. At a specific pump power level NA needs to be optimized to reach a peak performance. For example, at a 250mW pump power the fiber with NA of 0.18 gives an optimal performance. To show NA effect more clearly, the result of PCE versus NA at different pump powers is shown in Figure 2. The result shows that for pump power of 125mW and 275mW a fiber with NA of 0.23 and 0.18 respectively is optimal. This is consistent with experimental results, which will be shown in the next section.

Another fiber parameter, fiber cutoff wavelength, is a critical factor for optimal fiber performance. Higher cutoff improves the overlap between erbium ions and optical mode field. Fig. 3 shows power conversion efficiency for two different fiber designs. The peak efficiency difference between these two fibers is mainly attributed to erbium concentration difference due to different cutoff wavelengths. The fiber parameters used in the calculated and other predicted ones are shown in Table 1. The result clearly shows that fiber #2 has significantly better efficiency than fiber #1 in high power region. The efficiency difference is over 10% at 500mW pump power level. However, fiber #2 under-performs fiber #1 in low power region as expected.

Fig. 4 shows the simulation results of gain and NF for these two fibers as a function of pump power with a fixed input signal power of 0dBm at 1550nm. The fiber length is 16m for both cases. Fiber #2 again is significantly outperforms fiber #1 at high pump power. NF is equivalent for both fibers at high pump power. However, in low pump power region, fiber #1 performs better than fiber #2 in both gain and NF.

Table 1 Fiber parameters of two different fiber designs

	Fiber #1	Fiber #2	Unit
Peak absp around 1530nm	6.5	6.5	dB/m
Numerical aperture	0.22	0.18	
Cutoff wavelength	900	1100	nm
Mode field diameter @ 1550nm	6.0	6.8	µm
Core diameter	3.1	4.7	µm

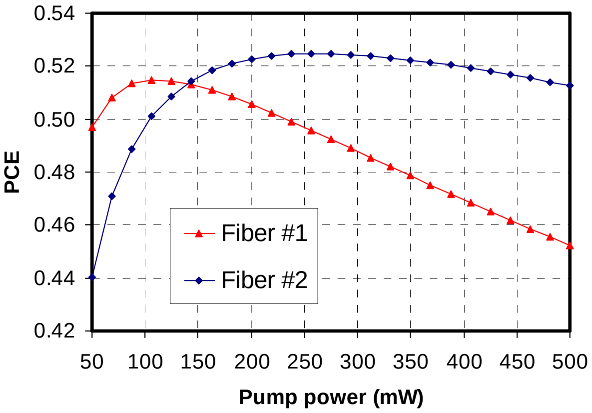

Fig. 3 PCE for two different fiber designs

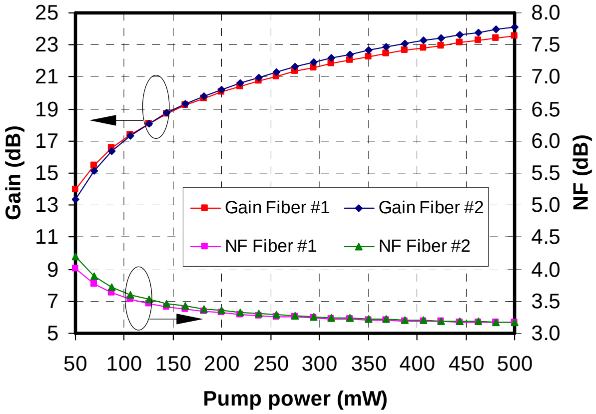

Fig. 4 Gain and NF comparison (15m fiber length)

Doping composition plays a critical role in EDF's spectral characteristics. Higher aluminum content is known to improve gain spectral flatness, as well as fiber efficiency by reducing clustered pairs of erbium ions. Previous fiber with low NA (e.g. HP980 of OFS) has a low aluminum concentration around 6 mol%. It does not have flat spectral shape. Therefore, this fiber is not suitable for wide band WDM operation.

2.3 High Power EDF Characteristics

Based on the above design, we have developed a new EDF with NA and cutoff around 0.18 and 1100nm, repectively. The fiber parameters are shown in Table 2. The peak erbium absorption around 1530nm is measured to be 7.4 dB/m. Background loss at 1550nm is 0.5dB/km. Numerical aperture and cutoff wavelength are 0.176 and 1140nm, respectively.

This fiber also has high aluminum concentration through a new EDF manufacturing process via MCVD. The aluminum concentration of the fiber is estimated to be greater than 12 mol%. To evaluate the gain spectral shape characteristics, we have measured the absorption $\alpha(\lambda)$ and small signal gain $g^*(\lambda)$ of this fiber and compared with other commercially available EDFs, MP980 and HP980 made by OFS. The gain shape is calculated using average inversion method with the following equation.

$$G(\lambda, Inv) = [g^*(\lambda) \cdot Inv - (1 - Inv)\alpha(\lambda)]L \qquad (5)$$

where G is the gain, Inv is average inversion level of erbium ions, and L is the fiber length.

The measured absorption α and small signal gain g* are shown in Fig. 5. The gain shape comparison with other two fiber types, MP980 and HP980, is shown in Fig. 5. In the gain shape calculation, the gain at 1565nm and minimum gain at around 1538.5nm are kept to be 20dB. So gain tilt is zero between these two points for the sake of convenience. As shown in the graph, the flatness of the new fiber is significantly better than HP980. The flatness difference is over 1dB. The flatness of the new fiber is slightly better than MP980, a fiber which is ideal for WDM applications at medium power level.

Table 2 Characteristics of new high power EDF

	New Fiber	Unit
Peak absp around 1530nm	7.4	dB/m
Pump peak absp around 980nm	4.0	dB/m
Background loss at 1550nm	0.5	dB/km
Numerical aperture	0.176	
Cutoff wavelength	1143	nm
Mode field diameter @ 1550nm	6.7	µm
Core diameter	4.9	µm
Aluminum concentration	>12	mol%

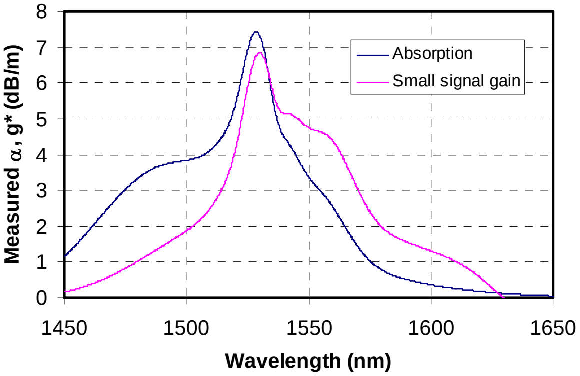

Fig. 5 Measured absorption and small signal gain

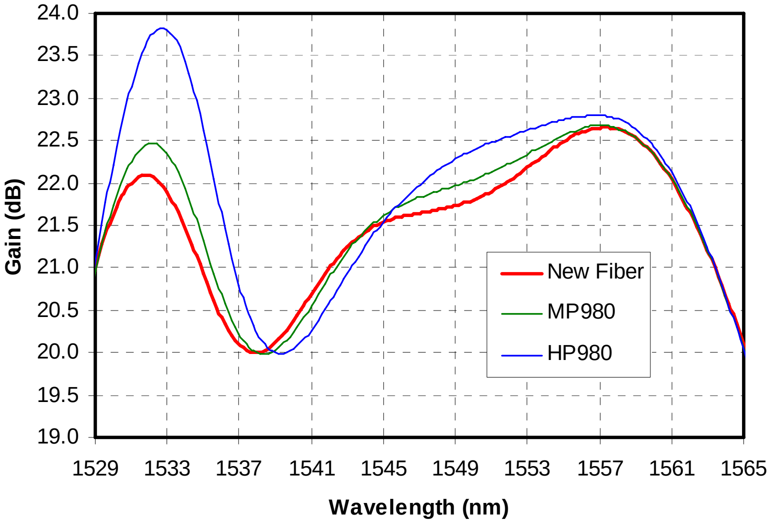

Fig. 6 Comparison of gain flatness of the new fiber with MP980 and HP980

EXPERIMENTAL RESULTS AND DISCUSSION

To determine the new fiber's actual performance, we measured the power conversion efficiency of this fiber as well as a typical MP980 fiber for comparison. In the measurement, a simple one-stage configuration with co-propagating pump was used. To obtain a high 980nm pump output power, two 980nm pumps were multiplexed together to achieve pump power of over 600mW at around 978nm. The input signal wavelength is 1550nm and the signal power is 0dBm. In the measurement, input and output splice losses were also measured and taken into account in the efficiency calculation. The experimental efficiency result shown in Fig. 7 clearly indicates that new fiber outperforms MP980 for pump power over 150mW, similar to the simulation prediction.

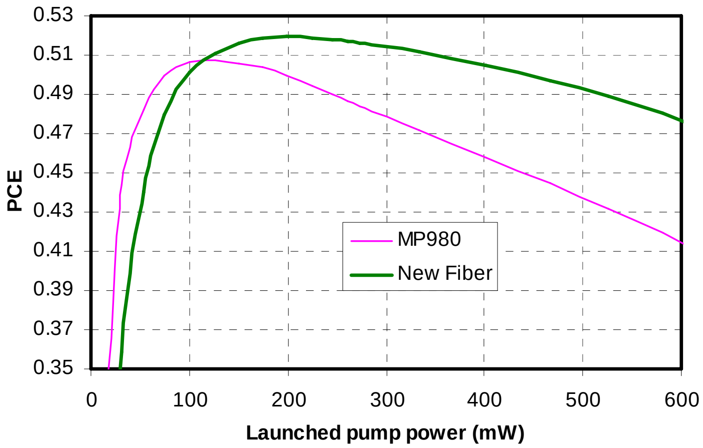

Fig. 7 Measured PCE vs. launched pump power for two fibers with
0dBm and 1550nm signal input

We also evaluated spliceability of this new fiber to typical pigtail fibers using typical splicers (e.g. Ericsson 995). Three pigtail fibers, Corning SMF28, OFS D980B-16, and Corning HI1060, were used in the evaluation. The splice loss was measured at 1305nm with an optimized splice program for each splice pair. The average splice loss for each measured splice pair is less than 0.1dB. A typical example of 10 consecutive splice losses between the new fiber and SMF28 are shown in Fig. 8. The average splice loss for this splice pair is 0.045dB, and the standard deviation of these 10 splice losses is 0.008dB.

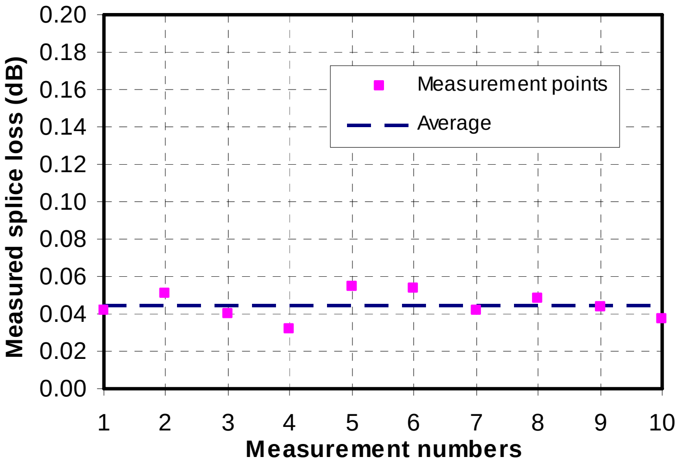

Fig. 6 Measured splice loss to SMF28 at 1305nm using Ericsson splicer 995

We also measured the macro-bending of the new fiber at two bending diameters, 38mm and 25.4mm, by making 10 turns at each diameter. The macro-bending loss at these two diameters in C-band wavelength range is not detectable, or within measurement limit.

One possible issue considered for the new fiber is that its cutoff wavelength is around 1100nm, which is higher than pump wavelength of 980nm. This fiber supports both LP_{01} mode and LP_{11} mode at 980nm. The presence of mode LP_{11} can negatively impact the fiber performance and will generally reduce the efficiency and cause instability of output power.

To check the possible presence of LP_{11} in EDF, we monitored the output power, which showed a stable result. In addition, we coiled the EDF to two different diameters, 38mm and 25.4mm at the EDF's signal and pump input end in the efficiency measurement, and monitored the output power variation. No noticeable output power variation between coiled and uncoiled conditions has been observed. Therefore, preliminary results indicate that the high cutoff fiber can work well for amplifiers with 980nm pumping.

CONCLUSIONS

We have presented a novel high power EDF, which features low numerical aperture to reduce non-linear effect and high aluminum concentration to enhance spectral flatness and fiber performance. The modeling and design of the high power EDF were illustrated. Fiber performance including power conversion efficiency and spectral gain flatness was shown and compared with other commercially available EDFs.

The performance results have shown that this EDF features high efficiency at high pump power, extremely flat gain spectrum, very low splice loss to typical pigtail fibers (e.g. average 0.045dB splice loss to SMF28), good macro-bending performance. The new EDF offers an ideal solution for C-band high power amplifier applications.

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