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L-BAND AMPLIFICATION AND MULTI-WAVELENGTH LASING WITH BISMUTH-BASED ERBIUM DOPED FIBER

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Abstract—Bismuth-based EDF (Bi-EDF) is comprehensively studied as an alternative medium for optical amplification. The bismuth glass host provides the opportunity to be doped heavily with erbium ions to allow a compact optical amplifier design. The gain spectrum of the Bi-EDF amplifier has a measured amplification bandwidth of 80 nm with a quantum conversion efficiency of 20% obtained using 1480 nm pumping and 215 cm long of doped fiber. A multi-wavelength laser comb is also demonstrated using a four-wave mixing effect in a backward pumped Bi-EDF. The laser generates more than 10 lines of optical comb with a line spacing of approximately 0.41 nm at 1615.5 nm region using 146 mW of 1480 nm pump power.

1. INTRODUCTION

Recently, Bismuth-based erbium-doped fibers (Bi-EDFs) have been extensively studied for use in compact amplifiers with short gain medium lengths. This fiber incorporates lanthanum (La) ions to decrease the concentration quenching of the erbium ions in the fiber [1], which allows the erbium ion concentration to be increased to more than 1000 ppm. A fiber with such a high erbium dopant concentration is expected to have enormous potential in realizing a compact erbium-doped fiber amplifiers (EDFAs) and EDFA based devices. The Bi-EDF also exhibits a very high fiber nonlinearity, which can be used for realizing new nonlinear devices such as wavelength converter and laser source [2, 3]. Multi-wavelength lasers are required for dense wavelength

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division multiplexing (DWDM) optical system, which is an enabling technology to fulfill a demand of bandwidth in the modern information age.

In this paper, the optical performance of the Bi-EDF amplifier (Bi-EDFA) is characterized and compared with that of Si-EDFA. Then, a multi-wavelength laser is demonstrated using the Bi-EDF assisted by FWM process.

2. CHARACTERIZATION OF THE Bi-EDF

The Bi-EDFA is characterised for its luminescence and lifetime properties and its gain and noise figure performance. In this Bi-EDFA, the Bi-EDF is bi-directionally pumped by a 1480 nm laser with total power of 288 mW. The Bi-EDF used in this experiment is commercially available from Asahi Glass Co and has an Er^{3+} ion concentration of 7.6×10^{25} ions/m^3 with a Lanthanum ion co-dopant concentration of approximately 4.4 wt%. The fibre used has a length of 181.9 cm, a core/cladding refractive index of 2.03/2.02 and a NA of 0.20. It is angle spliced to a single-mode fiber in order to reduce splice point reflections.

For the luminescence experiment, the two 1480 nm pump laser diodes are operated in CW mode while for the lifetime experiment the 1480 nm pumps are pulse modulated using a square-wave function generator at 70 Hz. The 1550 nm fluorescence spectra is measured using an optical spectrum analyser (OSA) and the lifetime of the erbium ion in the Bi-EDF is measured using the decay, which is detected using HP 83440B photodiodes with a digital oscilloscope. The decay oscillogram is transferred to a computer via General Purpose Interface Bus (GPIB) hardware, and the decay lifetime is obtained by fitting the single-exponential function to the experimental fluorescence decay curves. The gain and noise figure of the Bi-EDFA are also investigated. The experiment is then repeated using a 30 m commercially available Si-EDF from Fibercore Ltd. with an Er^{3+} doping concentration of 2.0×10^{25} ions/m^3 for comparison purposes.

Figure 1 shows the measured and calculated emission cross-section using the McCumber theory and also the Si-EDF emission cross-section as a comparison. The McCumber emission cross-section was calculated using absorption cross-sections provided by Asahi Glass Co, and it can be seen in the figure that the calculated emission cross-section agrees well with the experimental data. This optical emission peaks at the 1.53 μm, which is obtained due to the population inversion between energy level $^4I_{13/2}$ and $^4I_{15/2}$. Also from Fig. 1, it can be seen that the Bi-EDF has wider emission spectra as compared to Si-EDF, especially at the longer wavelengths at 1620 nm because of its larger emission cross-section. The Si-EDF has a bandwidth of only 40 nm while the Bi-EDF bandwidth is almost double at 80 nm for the same emission intensity. The widening of the emission spectra is believed to be a result of the Stark level of the Er^{3+} ions in the Bi-EDF, which is separated to a larger degree due to the larger ligand field as shown by the absorption cross-section. As shown in Fig. 1, despite the Bi-EDF having a higher absorption cross-section of $7.58 \times 10^{-25}\,\mathrm{m}^2$ at the 1530 nm peak as compared to the Si-EDF absorption cross-section (which is only $4.39 \times 10^{-26}\,\mathrm{m}^2$), the peak full-width half maximum (FWHM) of the Bi-EDF is narrower than the FWHM of the Si-EDF. This is due to the larger inhomogeneous energy level degeneracy that the ligand field of the Bismuth host glass induced as a result of site-to-site variations, also known as the Stark effect [4], causing the widened optical transitions. Other elements such as potassium oxide also have similar glass basicity expender effects [5] and are used in the fabrication of Bi-EDF to obtain a broader amplification region.

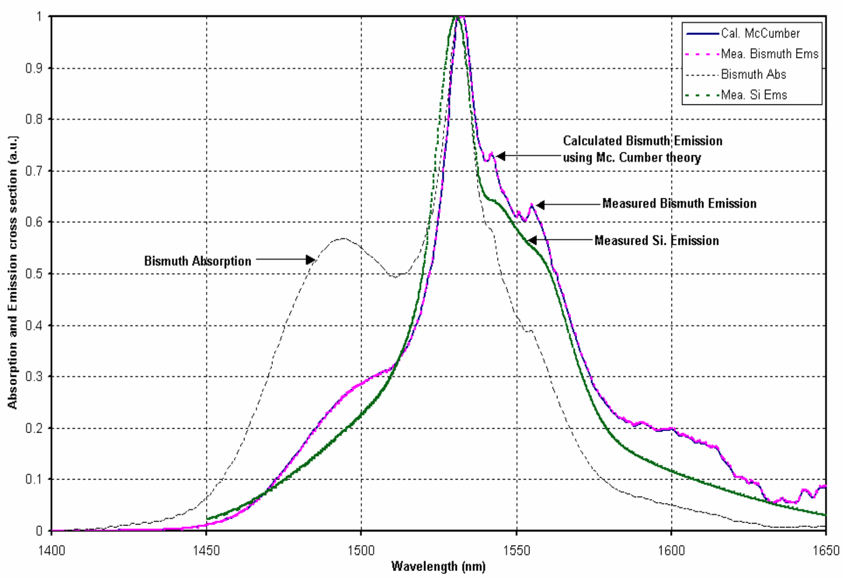

Figure 1. Absorption and emission cross-section of Bi-EDF and Si-EDF. (The Bismuth absorption cross-section is obtained from Asahi Glass Co.). The calculated Bismuth emission curve coincides very well with the measured curve.

Figure 2 shows the lifetime decay curve of Er^{3+} ions of Bi-EDF, which was measured at wavelength of 1530 nm. The decay curve is fitted with the single exponential decay function using the least square method as shown by the solid line. From the fitting curve, the lifetime of the erbium ion was measured to be approximately 2.84 ± 0.08 ms, which is shorter than that measured by Yang et al. [6] and much more lower than the compared lifetime of Er^{3+} ions in a silica host glass [4]. The quantum efficiency η and non-radiative transition rate W^{NR} at the 1550 nm emission are calculated to be 63.0% and $130.3\,s^{-1}$, respectively. This shows that the Bi-EDF is capable of generating the sought-after high population inversions with only a modest pump power [7]. Furthermore, this indicates that glass hosts with low phonon energies such as bismuth glass ($500\,cm^{-1}$) can be used to design an efficient optical amplifier with a wider fluorescence bandwidth [6, 7]. The wider fluorescence bandwidth is also attributed to the effect of the alumina and Lanthanum co-dopants towards the Er^{3+} ions distribution in the Bi-EDF which reduces the concentration quenching effect of the Er^{3+} ions, thus increasing the quantum efficiency [8, 9].

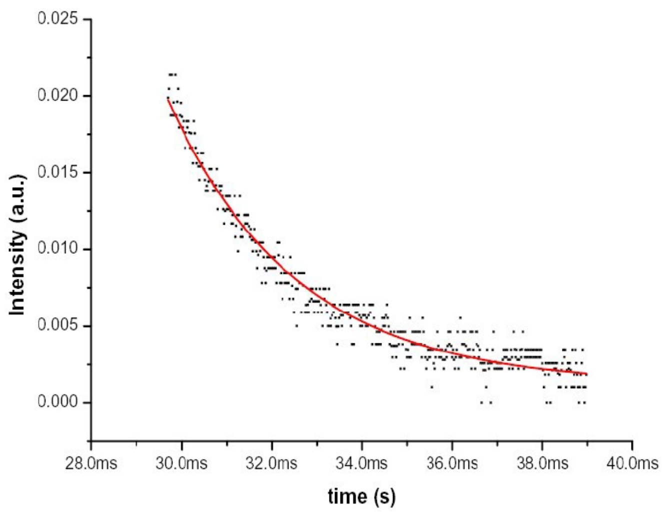

Figure 2. The measured lifetime of the erbium ion in Bi-EDF at 1530 nm. The fitting curve to the data is represented by the solid line.

The complete compositional analysis of the Bi-EDF glass is also investigated and measured using Energy Dispersive X-Ray Microanalysis (EDX) techniques. In this measurement, the sample is bombarded with electron energy accelerate at 20 kV and the emitted X-Rays from the sample are captured and analysed with the system software. Fig. 3 shows the measured energy spectrum of the Bi-

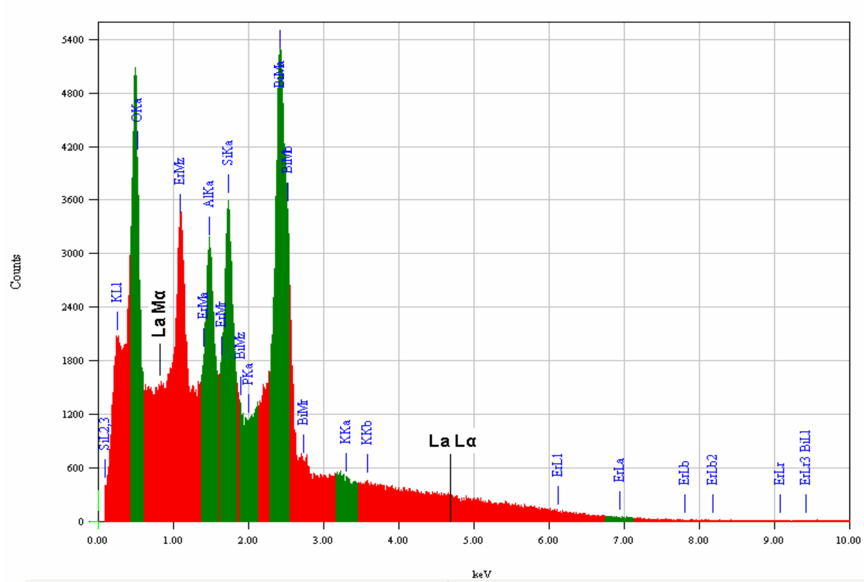

Figure 3. The measured energy spectra of the Bi-EDF using EDX.

EDF glass. In the experiment, an elemental analysis is performed using the bundled in software build-in with the ZAF method to calculate the errors. The complete compositional analysis of the Bi-EDF glass using EDX is summarized in Table 1. From the analysis, the glass network formers for the Bi-EDF are determined to be bismuth oxide, silica and alumina while the other markers are determined to be the glass network modifiers. The glass former is more prevalent elements in the glass structure than the glass modifier. By utilizing bismuth oxide and alumina as the main glass network former, the local glass basicity near the Er^{3+} ions sites is expanded as reported by Yang et al. [10] and Ainslie et al. [8], effectively increasing the crystal field (ligand field) of the glass. This has the result of enhancing the 1530 nm fluorescence full-width-half-maximum (FWHM) spectrum [8, 10] making it comparably broader than that obtainable with a silica glass host.

3. AMPLIFICATION CHARACTERISTICS

In order to gauge the behaviour of the Bi-EDF in optical amplification, then Bi-EDF optical amplifier characteristics and performance is evaluated by measuring the signal gain and noise figure. In this experiment, the Bi-EDF is bi-directionally pumped by a 1480 nm laser with total power of 288 mW. The gain (G) and noise figure (NF) are measured by an optical spectrum analyzer (OSA) using the following equations;

$$G(dB) = 10 \log_{10} \left(\frac{P_{out} - P_{ASE}}{P_{in}} \right) \tag{1}$$

$$NF(dB) = 10 \log_{10} \left(\frac{1}{G} + \frac{P_{ASE}}{h\nu \Delta\nu G} \right) \tag{2}$$

wher P_{in}, P_{out}, and P_{ASE} are the input power, the output power and the amplified spontaneous emission power (ASE) power, respectively. h is the photon energy and is the OSA's resolution. Fig. 4 compares the gain and noise figure of the Bi-EDFA with the Si-EDFA at input signal of 0 dBm. The gain of the Bi-EDFA is approximately 3 dB or 50% higher than that of the Si-EDFA with a flat gain profile. The Bi-EDFA gain bandwidth is also wider by 15 nm than that of the Si-EDFA, to give the Bi-EDF gain bandwidth of approximately 80 nm spanning from 1540 nm up to 1620 nm. This 15 nm increase in the gain bandwidth represents the potential addition of 18 signal channels of a 100 GHz transmission system with the implementation of Bi-EDF optical amplifiers [11]. However, the high Er^{3+} ions doping concentration and high insertion loss of the Bi-EDF incur a higher noise figure penalty of approximately 2.6 dB than the noise figure penalty of a Si-EDF when spliced to a conventional SMF. This increased noise figure is attributed to the effect of multiple reflections from both the fibre splice points whereby the signal is reflected back into the Bi-EDF due to the large refractive index difference, causing multi-path interference (MPI) noise [4].

Figure 5 shows the quantum conversion efficiency (QCE) and

Table 1. The Bi-EDF glass composition analysis using EDX.

Element	Mass (%)	Error (%)
Bi_2O_3	67.80	1.88
SiO_2	14.24	0.81
Al_2O_3	16.96	0.87
K_2O	0.05	0.29
P_2O_5	0.53	0.64
Er_2O_3	0.42	1.67
Total	100.00	6.17

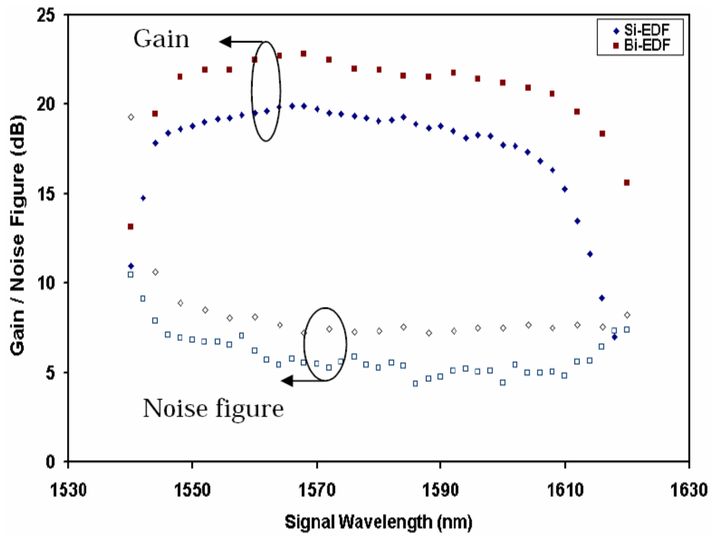

Figure 4. Comparison of the measured signal gain and noise figure at input signal power of 0 dBm between Si-EDFA and Bi-EDFA.

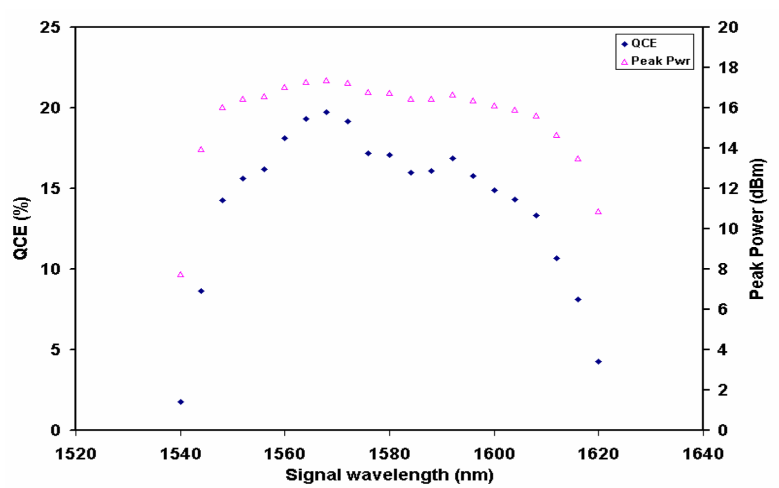

Figure 5. Measured QCE of 0 dBm input signal power from 1540 nm to 1620 nm for Si-EDF and Bi-EDF.

output power of the Bi-EDFA against signal wavelength. The QCE is pump wavelength independent and defined as [4]:

$$\text{QCE} = \left(\frac{\lambda_s}{\lambda_p}\right)\frac{P_s^{out} - P_s^{in}}{P_p^{in}} \tag{3}$$

where $\lambda_{p,s}$ are the pump and signal wavelengths, $P_s^{out,in}$ are the signal output and input powers and P_p^{in} is the pump power. From energy conservation principles, the maximum value for the QCE is unity when:

$$\frac{P_s^{out} - P_s^{in}}{P_p^{in}} = \frac{\lambda_p}{\lambda_s} \tag{4}$$

The highest QCE is determined by Eq. (4) to be approximately 19.7% at 1568 nm while the lowest QCE is calculated to be 1.7% at 1540 nm. The higher QCE in the Bi-EDF amplifier is due to the phonon energy of the glass host is much lower than the Er^{3+} ions energy gaps and this significantly reduces the pump photon energy loss to non-radiative emission [12]. Therefore, almost all the pump photons are converted to signal photons in the amplification process. With its high pump to signal conversion efficiency, the Bi-EDF is an efficient optical amplifier with shorter fibre length as compared to Si-EDF.

4. NONLINEAR CHARACTERISTICS

Beside a broadband amplification, the Bi-EDF also exhibits a very high fiber nonlinearity, which can be used for realizing new nonlinear devices such as multi-wavelength laser [13, 14]. A multi-wavelength laser is demonstrated using the Bi-EDF assisted by FWM process in a ring cavity resonator as shown in Fig. 6. The multi-wavelength laser resonator consists of the 215 cm long of Bismuth-based EDF (Bi-EDF), which is backward pumped using a 1480 nm laser diode, isolators, polarization controller (PC) and 10 dB output coupler. Wavelength division multiplexer (WDM) is used to combine the pump and laser wavelengths. Polarisation controller (PC) is used to control the birefringence in the ring cavity so that the output laser generated can be controlled and optimized. Two optical isolators are used to ensure unidirectional operation of the laser. A 10 dB coupler is used to tap the output of the laser via 10% port as shown in Fig. 1, which is then characterized by an optical spectrum analyzer (OSA) with a resolution of 0.015 nm. The operating wavelength of the multi-wavelength laser is determined by the backward pumped Bi-EDF gain spectrum which covers the long-wavelength band (L-band) region from 1570 to 1620 nm

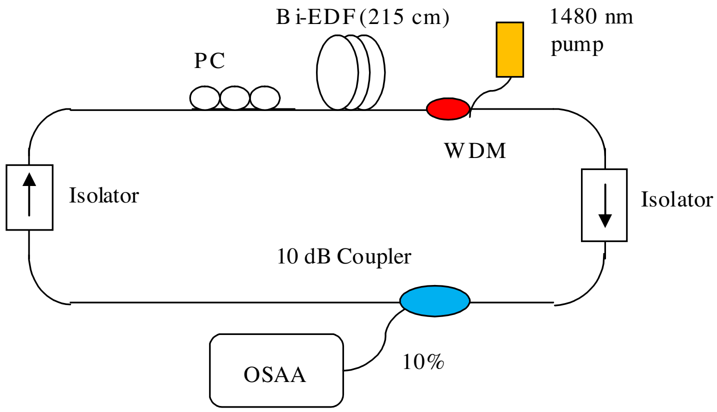

Figure 6. Experimental set-up for the proposed a Bi-EDF based multi-wavelength ring laser.

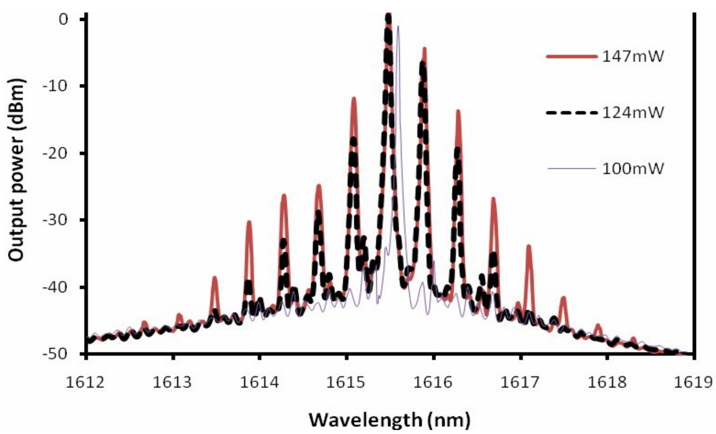

Figure 7. Output spectrum of the proposed Bi-EDF based multi-wavelength ring laser at different 1480 nm pump powers.

as well as the cavity loss. The Bi-EDF amplifier has small signal gain of approximately 30 dB at the L-band region with a pump power of 150 mW.

Figure 7 shows the output spectrum of the multi-wavelength laser for different 1480 nm pump power. As shown in the figure, the oscillating laser lines are observed in the 1615.5 nm region, which is fall within an extended L-band region. The amplification bandwidth of the Bi-EDF is extended to this region due to the suppression of excited-state absorption (ESA). The laser operates at this region due to the cavity loss which is lower at the longer wavelength. The backward pumped Bi-EDF generates amplified spontaneous emission at this region which oscillates in the ring cavity to generate at least two oscillating lines with a constant spacing due to the longitudinal modes interference. The strong forward oscillating laser generates a backward propagating reflected light in the gain medium (due to scattering and Fresnel reflection) to form a standing wave which interferes each other to form a multiple modes. The multi-wavelength laser generation with a constant spacing is assisted by the four-wave mixing process, which annihilates photons from these waves to create new photons at different frequencies. A PC has been used to control the polarisation and the birefringence inside the cavity, which in turn control the number of line generated, channel spacing and the peak power.

As shown in Fig. 7, more than 10 lines are obtained at the maximum pump power of 147 mW. At the minimum pump power of 100 mW, the erbium gain is lower and only one strong oscillating laser is generated. Since another oscillating laser line is below the threshold of the FWM process and thus no additional frequencies lines were observed. The number of generated line as well as the peak power is observed to increase as the pump power for the 1480 nm laser diode increases which is attributed to the increment of the erbium gain with pump power. This situation provides sufficient signal power for the FWM process to generate additional lines. In this experiment, the strongest line has a peak power of approximately -2 dBm and the line spacing is measured to be around 0.41 nm, which is determined by the cavity length and the birefringence in the ring cavity. The number of lines is limited by the availability of the 1480 nm pump power or erbium gain, fiber nonlinearity and polarisation filtering effect in the linear cavity resonator. The multi-wavelength output is observed to be stable at room temperature with only minor fluctuations observed coinciding with large temperature variances.

5. CONCLUSION

The composition and characteristic of the Bi-EDF and its optical performance with 1480 nm excitation have been comprehensively studied. Compared to the current Si-EDF, the Bi-EDFA only requires a shorter length of active fibre to achieve amplification and can significantly reduce the complexity and cost of optical amplifier. The Bi-EDF is also capable of producing high quantum efficiency amplifiers that significantly benefits optical amplifier designers. The Bi-EDF also has a shorter 1530 nm emission lifetime due to the high refractive index and Er^{3+} doping concentration. In the proposed Bi-EDFA, the efficiency of 17.9% can be achieved with an amplification bandwidth of 80nm after being pumped at wavelength of 1480 nm. We have also demonstrated a multi-wavelength laser comb using a Bi-EDF fiber as both linear and nonlinear gain media. The multi-wavelength generation is due to oscillating Bi-EDF laser lines which interacts each other to create new photons at other frequency via four-wave mixing process. The generated laser comb has more than 10 lines at the maximum 1480 nm pump power of 147 mW with a constant spacing of approximately 0.41 nm.

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