Tunable wavelength generation in 1-micron region incorporating 16-channels arrayed waveguide grating (AWG)

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Tunable wavelength generation in the 1 μm region incorporating a 16-channel arrayed waveguide grating (AWG)

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Abstract
A tunable single- and dual-wavelength ytterbium-doped fiber laser, incorporating a 16-channel arrayed waveguide grating is proposed and demonstrated. The side mode suppression ratio from the proposed setup has an average value of 52.97 dB (single-wavelength generation) and 58.19 dB (dual-wavelength generation). The tunable dual wavelength ranged from 1039.98 nm to 1047.48 nm with wavelength spacing ranging from 0.50 nm to 7.5 nm. A stability test from the experiment shows a power variation of 0.8 dB, and a wavelength fluctuation of 0.02 nm indicates the stability and reliability of the proposed work.

Keywords: tunable wavelength, dual-wavelength, arrayed waveguide grating, ytterbium doped fiber laser

(Some figures may appear in colour only in the online journal)

1. Introduction
Tunable wavelength generation using a fiber laser has attracted much attention over the past few years thanks to prominent characteristics such as high thermal resistance, excellent beam quality and relatively high stability output [1]. Wide potential applications such as optical-based sensing, instrumentation, photonics device characterization and wavelength division multiplexing (WDM) systems for optical communications can be exploited using the wavelength tunability from the fiber laser [2–6].

The basic device behind the wavelength tunability of the fiber laser contains a gain medium and a wavelength selective filter, which has a comb-like spectrum. In the past few years, an erbium-doped fiber as gain medium has been a popular choice for wavelength tunability and generation in the region of 1550nm. Erbium-doped fiber lasers (EDFLs) are highly suitable for tunable wavelength laser operation by virtue of their low threshold, narrow line width, excellent compatibility with other optical devices and high optical signal-to-noise ratio [7]. Several techniques for a wavelength selection filter using EDFLs have been reported in the literature, some of which include use of a Mach–Zehnder interferometer [8], fiber Bragg gratings (FBGs) [9], multi-mode fibers [10–12] and distributed Bragg reflectors [13, 14]. A wavelength selective filter is an important component in achieving a lasing wavelength, as it reduces mode competition by suppressing mode hopping in the laser cavity. By fine-tuning, this filter can generate a well-controlled single- to multi-wavelength lasing output.

More recently, there has been growing attention to the 1060 nm wavelength region incorporating ytterbium-doped fiber (YDF). Despite substantial attention, few reports exist on generating tunable single wavelengths in the 1060 nm region,
which is the motivation of this paper. Wavelength selective filters such as FBGs \cite{15, 16} and polarizing beam splitters have been reported as a tunable element for wavelength generation in YDF lasers (YDFLs) \cite{17}. YDF is an attractive gain medium for fiber lasers due to its high efficiency and strong absorption; these features additionally act as justification for further study of YDFLs. Tunable wavelengths in YDFLs are important for optical applications such as spectroscopy, sensing and coherence tomography \cite{18}.

A simple YDFL incorporating an arrayed waveguide grating (AWG) within a laser cavity to attain tunable single- and dual-wavelength operation is proposed and demonstrated in this paper. Experimental results show that 16 different wavelength outputs were achieved, corresponding to 16 channels of the AWG, with wavelengths ranging from 1038.8 nm to 1047.8 nm. The tunable wavelength outputs had an average side mode suppression ratio (SMSR) value of 52.97 dB (for single-wavelength generation) and 58.19 dB (for dual-wavelength generation). Both experiments recorded a fluctuation of power at approximately 0.8 dB, scanned over a 20 min period, indicating a stable system for tunable wavelength generation for fiber lasers.

2. Experimental setup

The laser cavity setting of the tunable single- and dual-wavelength output incorporating AWG is shown in figure 1. The single-wavelength setup is shown in figure 1(a), whilst the dual-wavelength ring setup is given in figure 1(b).

In the single wavelength configuration, a laser diode (Oclaro Model LC96A74P-20R) operating at 974 nm acts as a pump source with 600 mW of output power (maximum) and 40 mW of launched power. The output of the laser diode is connected to a 980/1060 nm WDM coupler. One output port of the WDM was fusion spliced to a 70 cm length of YDF gain medium (DF1100 Fibercore) that had peak absorption of 1300 dB m$^{-1}$ at 977 nm and attached to the input of the AWG. This AWG possessed 16 output channels, allowing 16 different outputs to be generated from the device, and it performed as a multiplexer that sliced the amplified spontaneous emission (ASE) source into 16 different channels in the 1 $\mu$m region. The insertion loss for the AWG was around $\sim 14$ dB, which is high due to its optimization specification in the 1550 nm region. The output port of the AWG, from channel 1 up to channel 16, at one output channel at a time, was attached to the input of an optical coupler (a 90/10 type), represented as OC in figure 1(a). The 10% output from the coupler was connected to a YOKOGAWA AQ6373 optical spectrum analyzer (OSA) with 0.02 nm optical resolution. The 90% port of the optical coupler was used to provide feedback for the laser by connecting it to the polarization insensitive isolator in a clockwise direction.

In the dual-wavelength configuration, two of the output ports from the AWG are connected to the 50/50 optical coupler, symbolized as OC1. The other end of the coupler was linked to a polarization insensitive isolator to ensure unidirectional transmission in the laser cavity. The isolator output was linked to a polarization controller (PC), which allows modifying the polarization state of the laser. The output of the PC was attached to the 90% port of the optical coupler, denoted as OC2. The 10% output from the coupler was attached to the input port of a YOKOGAWA AQ6373 OSA with 0.02 nm optical resolution.

3. Results and discussion

3.1. Tunable single wavelength

The YDFL-AWG unpolarized ASE transmission spectrum entering the AWG filter, the ASE source, was subsequently ‘sliced’ into 16 different wavelength channels. The output spectrum of 16 different wavelength channels is shown in figure 2. The wavelength outputs had a 9 nm tuning range starting from 1038.8 nm (channel 16) up to 1047.8 nm (channel 1) with a narrow band transmission. The spacing range between two adjacent channels was 0.6 nm. For the stable laser performance, the pump power for this experiment was set to 275 mW.

Figure 3 shows the output power from all 16 different wavelengths as measured from the optical power meter. It can be seen that the output power slightly increased with increases in wavelength, due to the power variations inherent in the wavelength-dependence gain of the YDF. The recorded average output power was $-15.03$ dBm with a maximum variation of 2.47 dB. From the results, channel 3 recorded the highest peak power of $-14.05$ dBm while channel 15 recorded the lowest peak power value of $-16.52$ dBm.

Figure 4 shows the SMSR measurement taken from each of the 16 AWGs’ wavelengths. The average SMSR value of 52.97 dB with maximum difference of 2.47 dB was obtained
from the experiment. Similar to the peak power measurement, channel 3 and channel 5 recorded the highest and the lowest values of SMSR at 53.95 and 51.48 dB, respectively. The high stability of the laser, as evidenced by the results in figure 4, can be explained by the large difference between the output power and the ASE level whereby each wavelength’s SMSR was higher than 50 dB.

Figure 2. Tunable laser wavelength by using 16 channels of an AWG.

Figure 3. Output power versus wavelength.

Figure 4. SMSR of the tunable YDF laser.

Figure 5 indicates the power measurement of the AWG for channel 1 and channel 16. The lasing started to occur at channels 1 and 16 with launching powers of 58 mW and 65 mW, respectively. The full width half maximum (FWHM) for each wavelength is shown in figure 6. The average value of the FWHM was 0.36 nm. The requirement for WDM systems to possess an upper limit of 0.6 nm maximum inter-channel spacing is easily surpassed via the small FWHM obtained from this experiment.

In addition to the wavelength characteristics detailed here, a stability test was performed over the shortest and longest wavelengths recorded from the AWG. The stability test was conducted over a period of 20 min. Figures 7 and 8 show the stability performance of two wavelengths, these being the shortest wavelength at channel 16 and the longest wavelength at channel 1. Figures 7(a) and 8(a) display a steady lasing wavelength, and figures 7(b) and 8(b) illustrate power variation throughout the scan. The results show that the maximum wavelengths and power fluctuation for both channel 1 and 16 were less than 0.02 nm and 0.8 dB, respectively, with the average output power for channel 1 being −14.45 dBm and for channel 16 − 16.37 dBm. Such findings provide evidence for the high stability of the system and minimal power variation at normal room temperature. The measurements of the tunable single-wavelength were conducted concurrently to the stability of the recommended setup.
In comparison to the similar approach reported in [15–17], the proposal demonstrated in this paper achieved a comparable SMSR and lasing threshold using a simpler setup and less equipment for the tunable wavelength output. Furthermore, work in [15, 16] employed a tunable FBG as wavelength filter, for which fabrication requires expensive equipment such as a UV laser and phase mask, in contrast to the significantly lower costs for AWG fabrication. The wavelength generated with the AWG is discrete. However, with the FBG, the wavelength can be continuously tuned, which is required in some applications. Therefore, the AWG used in the work described within this paper proves to be an excellent choice as a wavelength selector for tunable wavelength in the 1 µm region.

3.2. Tunable dual wavelength

In this part of experiment, the maximum pump power was set to 285 mW for stability purposes and for better performance

Figure 7. (a) Wavelength stability, and (b) output power stability performance for channel 1 (1047.8 nm) taken over 20 min.

Figure 8. (a) Wavelength stability, and (b) output power stability performance for channel 16 (1038.8 nm) taken over 20 min.

Figure 9. Tunable dual-wavelength laser spectrum of the AWG with increasing wavelength spacing.
of the laser. By using the 3 dB coupler and by adjusting the PC, the generation of a dual-wavelength in the AWG was successfully achieved. The PC was used in this experiment to adjust the peak output power of lasing, so that the balanced dual-wavelength lasing output can be obtained. The output of the dual wavelength can be realized by fixing one source channel (channel 1) and another source to be selected from the remaining 15 channels. The range of the generated dual-wavelength output obtained from the experiment was 0.50 nm (channel 1 and 2) to 7.5 nm (channel 1 and 16). By exchanging the channel of the AWG from channel 2 to 16, the wavelength spacing between adjacent channels was uniformly increased (in multiples of 0.50 nm). This result is shown in figure 9, due to the AWG’s 70 GHz inter-channel spacing. Alternatively, operating the AWG with smaller inter-channel spacing within the region of 25 GHz can narrow down the spacing between the wavelength channels. The SMSR, together with the peak power of the dual-wavelength output from channels 1–16, equaled a total of 15 time sweeps from channel 2 to channel 16, with one output port fixed at channel 1. The SMSR variance of the dual-wavelength laser was 1.2 dB with an average SMSR of 58.19 dB, whereas the maximum difference of the SMSR and peak power was 3.47 dB and 4.03 dB, respectively. The variance and average in output power was 1.2 dB and −6.81 dBm respectively.

Figures 10(a) and (b) shows channel 1 and channel 8 having a very stable lasing dual wavelength with adjacent wavelength spacing of 3.5 nm ($\lambda_1 = 1047.48$ nm and $\lambda_2 = 1043.98$ nm), and figures 11(a) and (b) illustrate channel 1 and channel 16 with stable dual wavelength with adjacent spacing of 7.5 nm ($\lambda_1 = 1047.48$ nm and $\lambda_2 = 1039.98$ nm) over a period of 20 min. Both results show that the power fluctuation was less than ~0.4 dB and this proves the stability of the proposed system. The measurements of the switchable dual wavelength were conducted concurrently, to confirm the stability of the recommended setup. From this measurement, the proposed setup stability performance is better than reported by [19], which shows that the AWG is a reliable filter to generate very stable dual-wavelength lasing with the added advantage of wide wavelength selection.
4. Conclusion

This paper described in detail a successful demonstration of tunable single- and dual-wavelength operation utilizing a 70 cm YDF and AWG. The proposed setup for single wavelength lasing resulted in the generation of 16 single wavelength results had a fluctuation of power less than 0.8 dB over 20 min scanning time, which indicates a very stable system for a switchable and tunable wavelength in fiber laser.

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