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Optically Modulated Tunable O-Band Praseodymium-Doped Fluoride Fiber Laser Utilizing Multi-Walled Carbon Nanotube Saturable Absorber *

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A tunable and optically modulated fiber laser utilizing a multi-walled carbon nanotube based saturable absorber is demonstrated for operation in the O-band region. A praseodymium-doped fluoride fiber is used as the gain medium and the system is capable of generating modulated outputs at 1300 nm. Pulsed output is observed at pump powers of 511 mW and above, with repetition rates and pulse widths that can be tuned from 41 kHz and 3.4 μs to 48 kHz and 2.4 μs, respectively, at the maximum pump power available. A maximum average output power of 100 μW with a corresponding single pulse energy of 2.1 nJ is measured, while the tunability of the proposed laser is from 1290 nm to 1308 nm. The output is stable, with peak power fluctuations of ∼4 dB from the average value.

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The second communication window, which is also known as the O-band region, is a highly efficient optical communication band due to the near zero dispersion characteristics in this wavelength region. Thus, the O-band region has been the focus of significant research efforts to support the development of new optical communication technologies that can cater to the ever-increasing demand for bandwidth, especially in last mile applications. In this regard, praseodymium-doped fluoride fibers (PDFFs) have emerged as a highly effective gain medium for O-band applications, with an operating wavelength centered at 1300 nm. Utilizing the $^3H_4$–$^1G_4$ transition at a pump wavelength of 1020 nm, praseodymium ions (Pr^{3+}) show no competing transitions leading to amplified spontaneous emission (ASE).[1−5] The Pr^{3+} ions in fluoride glass also overcome the limitations of strong excited state absorption (ESA) influence by the glass host and the subsequent build-up of ASE around 1050 nm, a problem commonly encountered with neodymium ions (Nd^{3+}), which also have a fluorescence band near 1300 nm.[1] Therefore, PDFF-based amplifiers would have significant applications in communication systems operating in the O-band region, and laser systems designed using PDFFs would also find significant applications not only as sources for telecommunications but also for material processing,[6,7] medicine[8] and sensing.

Modulation can be typically achieved in fiber lasers through active or passive means. Active techniques require the use devices as acousto-optic[9] and electro-optic[10−12] modulators into the laser cavity, which would vastly increase not only the complexity of the fiber system but also its cost. In contrast, passive techniques have a simple structure, giving flexibility in all fiber-designs, as well as ensuring a lower development cost. Semiconductor saturable absorber mirrors (SESAMs) were the earliest approach towards generating passively pulsed outputs in fiber lasers.[13−15] SESAMs offer better control over various absorber parameters, but still suffer from a number of drawbacks that range from complexity in cavity design to high fabrication cost.[16] Consequently, attention has now turned to thin film-based saturable absorbers (SAs) that can be used to modulate optical signals while at the same time being inexpensive and allowing for a compact fiber laser system to be realized. In this regard, single-walled carbon nanotubes (SWCNTs) have been widely investigated as a viable SA.[17] Since its discovery by Iijima in 1991,[18] CNTs have been determined to possess highly desirable opto-electronic characteristics such as an ultrashort recovery time, low production cost and a wide absorption bandwidth from 1000 nm to 2000 nm.[19−23] Multi-walled carbon nanotubes (MWCNTs) also possess many of these characteristics and have in fact become a more viable and popular candidate for fabricating SAs due to their lower production cost.[24] The fabrication of MWCNTs does not involve complicated techniques or special growing conditions, thus making it between 20%–50% less expensive than SWCNTs.[25] Furthermore, the multiple-wall structure of MWCNTs makes them less sensitive to environmental perturbations as compared to SWCNTs, thereby creating more stable modulated outputs.[26,27]

However, SWCNTs and MWCNTs have been widely used to generate mode-locked and modulated outputs from fiber lasers, in particular the S-band, C-band, L-band and 2000 nm regions,[20,28−32] little to no attention has been paid to generation of modulated laser outputs operating in the O-band region using either SWCNT or MWCNT based SAs. In this work, a passively modulated PDFF based fiber laser operating at O-band region with a tunable output is

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demonstrated. The laser uses an MWCNT based SA to modulate the signal generated in the cavity and this is, to the best of our knowledge, the first demonstration of a PDFF with a modulated optical output using an MWCNT as an SA.

The setup of the proposed modulated PDFF based laser is shown in Fig. 1. The SA is integrated into a laser cavity with a 11.7 m PDFF acting as the gain medium. The PDFF has an absorption coefficient of 3 dB/m at 1020 nm, a mode-field diameter of 4.2 μm at 1300 nm as well as a numerical aperture value of 0.26. The PDFF is pumped by a 1020 nm laser diode (LD) through the 1020 nm port of a 1020/1310 nm wavelength division multiplexer (WDM). The amplified output from the PDFF is transmitted through an optical isolator (ISO) to ensure unidirectional propagation inside the cavity, and from there guided into the SA which modulates the signal. To provide the cavity with the ability to tune the output wavelength, a tunable bandpass filter (TBPF) is integrated into the cavity between the SA and the output coupler. Approximately 5% of the modulated signal is extracted from the cavity through the 5% port of a 95:5 optical coupler (OC) for further analysis, whilst the remaining signal is connected to the 1310 nm port of the WDM, thus completing the optical cavity.

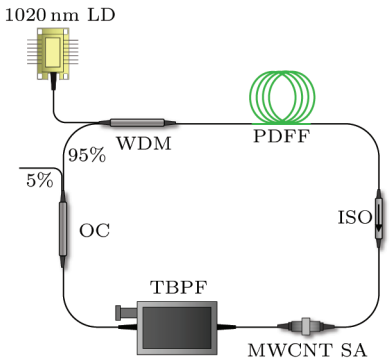

Fig. 1. Cavity configuration of PDFF laser.

The performance of the PDFF laser is investigated using an Anritsu AQ6370B optical spectrum analyzer (OSA), a Yokogawa DLM2054 oscilloscope (OSC) and an Anritsu MS2683 radio-frequency spectrum analyzer (RFSA).

The fabrication of the MWCNT based SA has been discussed in detail.[30] The proposed laser is initially operated without the TBPF and the SA in the cavity, and in this configuration, a continuous wave (CW) threshold power of 218 mW is observed. With the SA incorporated into the cavity, a modulated output is now obtained at a threshold power of 511 mW. The optical and temporal characteristics of the proposed modulated PDFF laser are given in Figs. 2(a)–2(c), with the traces obtained at the highest pump power of 567 mW. Figure 2(a) shows the optical spectra of the laser under both CW and modulated conditions. The modulated signal spectrum is centered at 1300 nm and is observed to be broader than the CW spectrum which has a 3-dB bandwidth of 2.16 nm. The broad spectrum is a typical characteristic of optically modulated signals and is ascribed to the self-phase modulation effect.[33,34] The temporal trace of the modulated laser output is shown in Fig. 2(b) with a repetition rate of 48 kHz, while the spectrum in Fig. 2(c) represents the modulated output in the frequency domain. In this spectrum, the observed peak corresponds to the fundamental frequency of the output signal at 48 kHz. From the same spectrum, the signal-to-noise ratio (SNR) is measured to be 35 dB, indicating that the modulated laser operates under a stable condition.

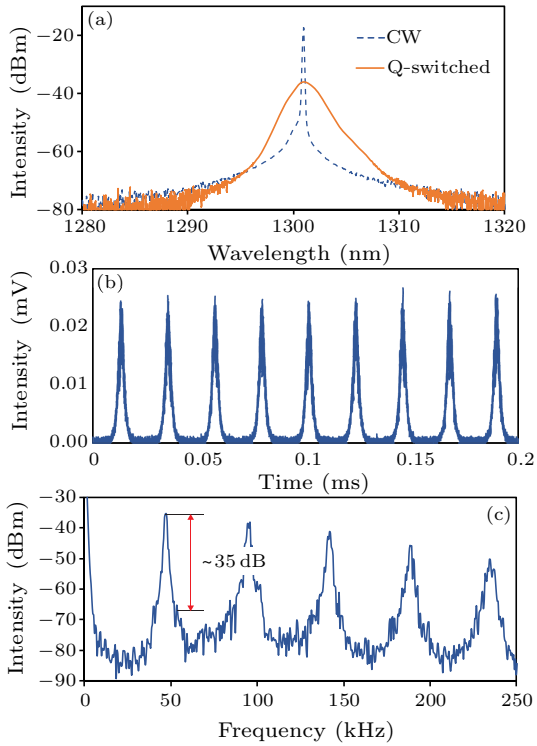

Fig. 2. (a) Optical spectra, (b) optical pulse train, and (c) radio frequency spectrum of the modulated laser.

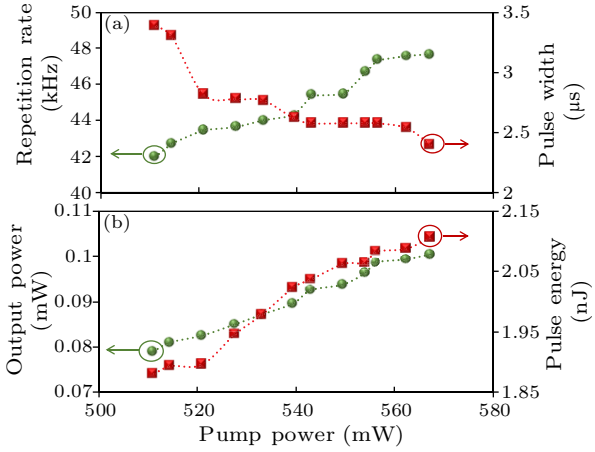

Fig. 3. Performance of Q-switched PDFF based laser as a function of pump power: (a) Repetition rate and pulse width, and (b) average output power and pulse energy.

Figure 3(a) shows the pulse repetition rate and pulse width as a function of the pump power. As

the pump power increases, from 511 mW to 567.2 mW, the repetition rate also increases steadily from 41 kHz to 48 kHz, giving the output repetition rate a tuning range of 7 kHz. Meanwhile, the pulse width shows a decreasing trend from 3.4 μs to 2.4 μs over the same pump power range. These results clearly illustrate the dependences of the pulse repetition rate and pulse width on the pump power that is attributable to the nonlinear dynamics in the gain medium and the SA.[35,36] Additionally, the average output power and corresponding single pulse energy are recorded and plotted in Fig. 3(b). From the figure, it can be seen that values gradually increase with the pump power, with the maximum average output power and pulse energy obtained to be 100 μW and 2.1 nJ, respectively. The pulse energy can be improved by further optimizing the laser cavity's coupling ratio and cavity length. Despite having a relatively low output power and pulse energy as compared to reported works using the same SA as in Table 1, this would be the first work involving the use of MWCNTs as an SA in an O-band fiber laser.

Table 1. Previous works on Q-switched utilizing MWCNT as SA.

Operating wavelength (nm)	Repetition rate (kHz)	Minimum pulse width (μs)	Maximum pulse energy (nJ)	Reference
2000	15.5	7	82.6	[32]
1563	20	8.8	15.3	[29]
1300	48	2.4	2.1	This work

The TBPF, with an insertion loss of 1.94 dB is then incorporated into the laser cavity to enable the tuning of the lasing wavelength. Figure 4(a) shows the modulated output spectra over a wavelength range of 1290 nm–1308 nm at the highest pump power.

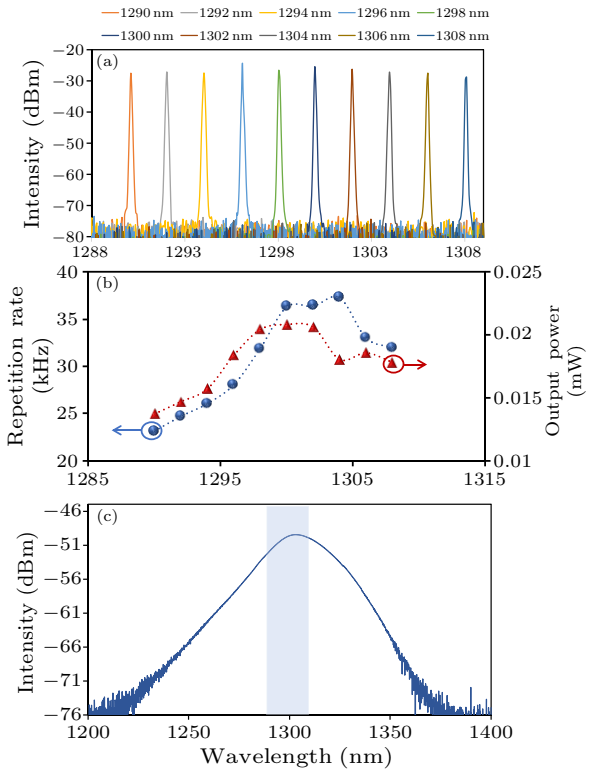

Fig. 4. (a) Laser output spectra at different wavelengths. (b) Repetition rate and average output power as a function of central wavelength. (c) ASE spectrum of the laser (highlighted part is the tuning range where the Q-switching operation is stable, 1290 nm–1308 nm).

From the spectrum, 10 lasing wavelengths are obtained at an increment of 2 nm with peak power fluctuations of less than 4 dB. The repetition rate and the output power as a function of the central wavelength is illustrated in Fig. 4(b). The pattern obtained from the figure is due to the ASE gain curve as shown in Fig. 4(c). Figure 4(b) shows that from 1290 nm to 1300 nm, there is a gradual increase in the repetition rate until it reached the maximum value of 37.2 kHz obtained at 1304 nm. The high intracavity lasing will induce a high repetition rate at the larger-gain wavelength of the gain medium. This is a result of the faster bleaching of the SA due to the faster population inversion/depletion rates, therefore giving a higher repetition rate. Above this wavelength, the repetition rate begins to decrease, following the ASE pattern of the laser.

In summary, a tunable and optically modulated PDFF laser operating in the O-band region has been demonstrated. The laser uses an MWCNT SA to generate a modulated output while the TBPF is incorporated into the cavity to tune the output wavelength. The laser cavity uses a 11.7 m PDFF as a gain medium, and is capable of generating modulated outputs at a central wavelength of 1300 nm above a threshold pump power of 511 mW. The pulses have repetition rates and pulse widths from 41 kHz to 48 kHz and 3.4 μs to 2.4 μs, respectively, while the maximum average output power is recorded to be 100 μW with a corresponding single pulse energy of 2.1 nJ. The Q-switched laser can be tuned starting from 1290 nm to 1308 nm with peak power fluctuation of less than ∼4 dB, indicating a highly stable output.

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