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Multi-Wavelength Q-Switched Erbium-Doped Fiber Laser with Photonic Crystal Fiber and Multi-Walled Carbon Nanotubes

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Abstract**—**A simple multi-wavelength passively Q-switched Erbium-doped fiber laser (EDFL) is demonstrated using low cost multi-walled carbon nanotubes (MWCNTs) based saturable absorber (SA), which is prepared using polyvinyl alcohol (PVA) as a host polymer. The multi-wavelength operation is achieved based on nonlinear polarization rotation (NPR) effect by incorporating 50 m long photonic crystal fiber (PCF) in the ring cavity. The EDFL produces a stable multi-wavelength comb spectrum for more than 14 lines with a fixed spacing of 0.48 nm. The laser also demonstrates a stable pulse train with the repetition rate increases from 14.9 kHz to 25.4 kHz as the pump power increases from the threshold power of 69.0 mW to the maximum pump power of 133.8 mW. The minimum pulse width of 4.4 μs was obtained at the maximum pump power of 133.8 mW while the highest energy of 0.74 nJ was obtained at pump power of 69.0 mW.

Keywords**—**Multi-wavelength, Q-switched, multi-wall carbon nanotube, photonic crystal fiber.

I. Introduction

BOTH multi-wavelength and Q-switched EDFLs have wide applications in optical communications, sensors and instrumentations [1], [2]. There are many different methods have been proposed to achieve multi-wavelength lasing at room temperature such as cascaded stimulated Brillouin scattering [3], incorporating a semiconductor optical amplifier or raman amplifier and four-wave mixing (FWM) [4]. Recently, NPR [5] which can induce intensity dependent loss is also widely used for multi-wavelength laser generation. On the other hand, Q-switched EDFLs can be generated using either active or passive techniques. Compared with the actively Q-switched ones, passively Q-switched EDFLs have attracted much attention for their advantages of compactness, low cost, flexibility and simplicity of design. Different kinds of saturable absorbers, such as the transition metal-doped crystals and semiconductor quantum-well structures [6], have been applied to realize Q-switched EDFL. However, when they are used in the laser cavity, additional alignment devices, such as lens, mirrors or U-bench units, have to be applied. This may increase the insertion loss and the complexity of the laser cavity.

When Over the last few years, the use of single-walled carbon nanotubes (SWCNT) material as a SA has been widely investigated in Q-switched fiber lasers [7]. This is due to their inherent advantages, including good compatibility with optical fibers, low saturation intensity, fast recovery time, and wide operating bandwidth, while the other types of crystal and semiconductor based SAs cannot be used for an all fiber laser structure due to their relatively big volume. Recently, MWCNTs [8] have also attracted considerable interest because they possess many advantages such as good thermal characteristics and ease in fabrication or growth. Compared with SWCNTs, the MWCNTs also have better mechanical strength, and higher photon absorption per nanotube due to its higher mass density of the multi-walls. These favourable features are due to the structure of MWCNTs which takes the form of a stack of concentrically rolled graphene sheets. The outer walls can protect the inner walls from damage or oxidation so that the thermal or laser damage threshold of MWCNT is higher than that of the SWCNT.

In this paper, a Q-switched multi-wavelength EDFL is demonstrated using a simple and low cost MWCNT-based saturable absorber, which is prepared using polyvinyl alcohol as a host polymer. The multi-wavelength operation is achieved based on NPR effect by incorporating 50 m long PCF in the ring cavity. The SA is integrated in the EDFL ring cavity by sandwiching the MWCNTs-PVA SA thin film between two fiber connectors to achieve a stable pulse train with 25.4 kHz repetition rate and 4.4 μs pulse width at 133.8 mW 1480 nm pump power.

II. Experiment Arrangement

In this work, the key part of Q-switching generation is the fabrication of saturable absorber incorporating dispersed MWCNTs. To match the EDFL operating at 1550 nm, the choosing of MWCNTs with suitable mean diameter and distributed diameter range is a critical step. In this work, we used SWCNTs with the purity of 99%, distributed diameter of 10-20 nm and length of 1-2 μm. The host material was PVA, which is a water-soluble synthetic polymer with monomer formula C_2H_4O. It has excellent film forming, emulsifying, and adhesive properties. It also has high tensile strength, flexibility, high oxygen and aroma barrier, although these properties are dependent on humidity. Firstly, the MWCNTs material is functionalized so that it can be dissolved in water. The functionalizer solution was prepared by dissolving 4 g of sodium dodecyl sulphate (SDS) in 400 ml deionized water. 250 mg MWCNT was added to the solution and the

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homogenous dispersion of MWCNTs was achieved after the mixed solution was sonicated for 60 minutes at 50 W. The solution was then centrifuged at 1000 rpm to remove large particles of undispersed MWCNTs to obtain dispersed suspension that is stable for weeks.

MWCNTs-PVA composite was prepared by adding the dispersed MWCNTs suspension into a PVA solution by 3:2 ratio. We prepared a PVA solution by dissolving 1 g of PVA in 400 ml distilled water. Then we mixed the PVA solution with the prepared MWCNTs solution to form the precursor and the mixture was stirred using ultrasonic cleaner for about one hour. This step helped us get precursor with enough viscosity so that it could be easily used in forming the MWCNTs-PVA film. Finally, suitable amounts of precursor were spread thinly on the glass substrate, and let dry in the room temperature to form the saturable absorber film. Raman spectroscopy was then performed on the MWCNTs-PVA film to confirm the presence of the carbon nanotubes. Fig. 1 shows the Raman spectrum, where obviously indicates the distinct feature of the MWCNTs such as a well-defined G and G' bands at 1580 cm^{-1} and 2705 cm^{-1}, respectively. We also see a prominent D band at around 1350 cm^{-1}, which indicates the presence of some disorder to the graphene structure. As expected, the prominent D band is also observed in Fig. 1, which indicates that the carbon nanotubes are of a multi-walled type, which has multi-layer configuration and disorder structure. In addition, others distinguishable features like G + B band (2920 cm^{-1}), a small peak at 854 cm^{-1} and Si were also observed as depicted in Fig. 1.

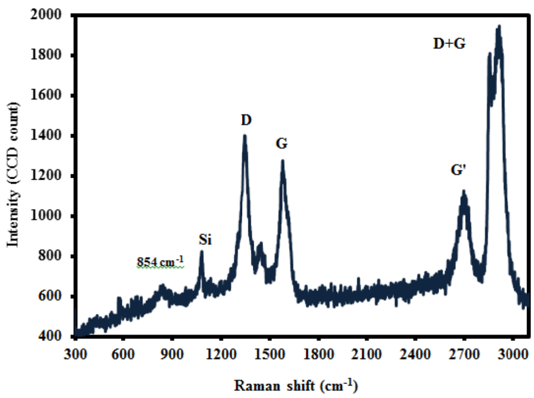

Fig. 1 Raman spectrum obtained from the MWCNTs-PVA film

The experimental set-up of the proposed EDFL is illustrated in Fig. 2, which the ring resonator consists of a 4.5 m long EDF as the gain medium, wavelength division multiplexer (WDM), polarization-dependent isolator (PDI), polarization controller (PC), PCF, MWCNTs-PVA SA and 10 dB coupler. The EDF used has an Erbium ion concentration of 2000 ppm, core diameter of 4 µm, mode field diameter of 6 µm and NA of 0.24. The SA is fabricated by cutting a small part of the earlier prepared film and sandwiching it between two FC/PC fiber connectors, after depositing index-matching gel onto the fiber ends. It is placed into the laser cavity to achieve saturable absorption that is required for the Q-switching operation. A 1480 nm laser diode is used to pump the EDF via the WDM. A PDI and PC are incorporated in the laser cavity to ensure unidirectional propagation of the oscillating laser and to act as a polarizer. The output of the laser is collected from the cavity via a 10 dB coupler which retains 90% of the light in the ring cavity to oscillate. The optical spectrum analyser (OSA, Yokogawa, AQ6370B) is used for the spectral analysis of the Q-switched EDFL with a spectral resolution of 0.02 nm whereas the oscilloscope (OSC, Tektronix,TDS 3052C) is used to observe the output pulse train of the Q-switched operation via a 460 kHz bandwidth photo-detector (PD, Thorlab PDA50B-EC).

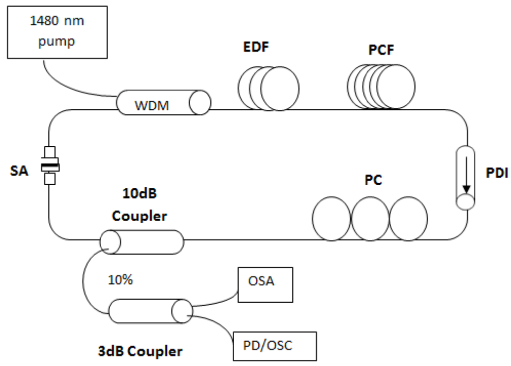

Fig. 2 Schematic configuration of the proposed multi-wavelength Q-switched EDFL

III. Results and Discussion

Firstly, the performance of the ring laser is investigated when a 50 m long PCF is excluded from the laser cavity. A self-started Q-switching of the laser occurs when the pump power is increased up to 50 mW but there are no multi-wavelength lasing is observed from the OSA as shown in Fig. 3 (a). The repetition rate is observed to be pump dependent, which indicates that the generated laser produces Q-switching pulse. As shown in Fig. 3 (b), the pulse train has the period of 20.8 µs, which corresponds to repetition rate of 48 kHz at pump power of 100.2 mW. The corresponding pulse width is around 5 µs. As a 50 m long PCF is incorporated into the cavity, a stable multi-wavelength laser with Q-switching operation was obtained at pump power threshold of 69 mW with a proper tuning of PC. This confirms that the multi-wavelength and Q-switched operations are mainly induced by the PCF and MWCNTs-PVA film based SA, respectively. Figs. 4 (a) and (b) show the measured multi-wavelength spectrum and typical Q-switched pulse train of the laser respectively, under pump power of 69 mW. As shown in Fig. 4 (a), the Q-switched laser produces at least 14 lines with free spectral range (FSR) of 0.48 nm, which is determined by the length and the effective group indices of the PCF. The multi-wavelength generation is due to the intensity dependent loss induced by NPR. The role of PCF is to increase the nonlinear effect as well as to constitute an inline periodic filter with the PDI. At the threshold pump power of 69 mW, the multi-wavelength laser produces a Q-switched pulse train with repetition rate of 14.9 kHz and pulse width of 7.1 µs as shown in Fig. 4 (b).

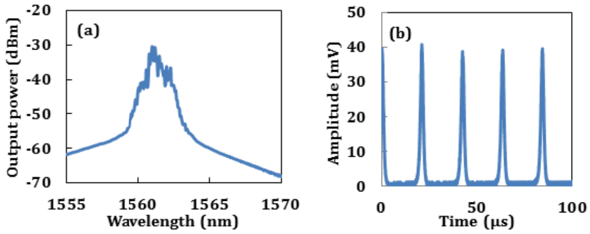

Fig. 3 Q-switching performance of the ring EDFL when the laser cavity excluded the 50 m long PCF, (a) Optical spectrum and (b) typical Q-switched pulse train when the pump is fixed at 100.2 mW

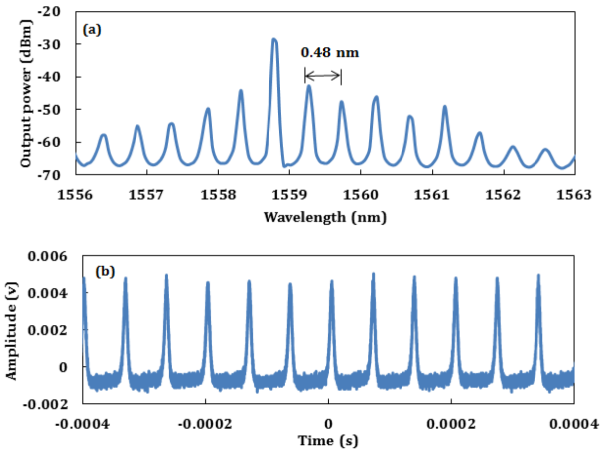

Fig. 4 (a) Optical spectrum and (b) Q-switched pulse train of the proposed multi-wavelength Q-switched EDFL when the pump is fixed at threshold power

The multi-wavelength generation is described as follows. The light is split into two orthogonal modes, which experience different nonlinear phase shift as they propogates inside the PCF owing to the Kerr effect. Then the polarization orientation of the light rotates in the PCF with the angle of rotation is correlative with the light intensity. The signal passes through the PDI, which the transmittivity is depended on the rotation of the polarization or the oscillating light intensity. The combination of the PCF and PDI functions an intensity equalizer, which produces an intensity dependent inhomogeneous loss and thus elleviates the mode-competition. As a result, the balance between the inhomogeneous loss induced by NPR and the mode competition effect of the EDF can lead to a stable multiwavelength oscillation. If the polarization state is selected properly by adjusting the PC, multiwavelength laser can be easily obtained. Fig. 5 shows the spectrum of the multi-wavelength laser against the pump power. As shown in the figure, the number of lines and its peak power increases with the pump power. However, the wavelength spacing is maintained at 0.48 nm for all pump powers. Note that the wavelength spacing can be tuned by changing the length of PCF. The Q-switching characteristic is obtained due to the SA. Fig. 6 shows evolution of the Q-switched pulse of the multi-wavelength against the pump power. As shown in the figure, the spacing between two pulses reduces with the pump power, which indicates Q-switching operation. It is also observed that the Q-switching operation is stable without any distinct amplitude modulation in each Q-switched envelop of the spectrum. This indicates that the self-mode locking effect on the Q-switching is unobservable and insignificant. At the maximum pump power of 133.8, the spacing between two pulses is measured to be around 39.3 µs, which can be translated to repetition rate of 25.4 kHz.

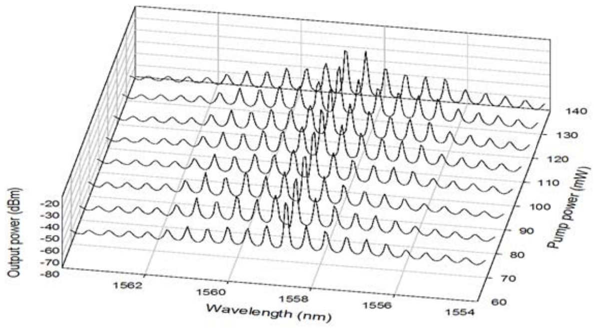

Fig. 5 Output spectrum evolution of the proposed multi-wavelength Q-switched EDFL against pump power

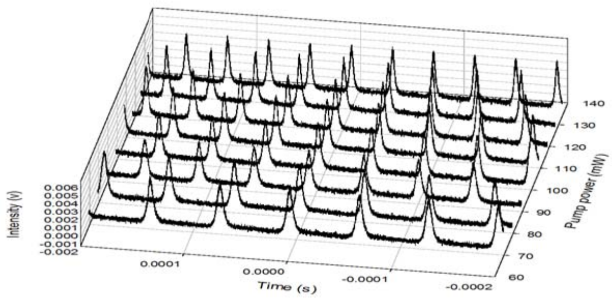

Fig. 6 Q-switched pulse evoluation of the proposed multi-wavelength Q-switched EDFL against pump power

Fig. 7 shows how repetition rate and pulse width are related to the pump power. The dependence of the pulse repetition rate can be seen to increase almost linearly with the pump power, while the pulse width decreases also almost linearly with the pump power. This agrees well with the passive Q-switching theory with the saturable absorber. The pulse repetition rate of the Q-switched EDFL can be widely tuned from 14.9 kHz to 25.4 kHz by varying the pump power from 69.0mW to 133.8 mW. On the other hand, the pulse width reduces from 7.1 µs to 4.4 µs as the pump power increases from 69.0mW to 133.8 mW. The pulse width is expected to drop further by further increasing the pump power, as long as the damage threshold of the SA is not exceeded. The pulse duration could also be reduced by using shorter highly doped EDF and further shortening the fiber between the components of the laser cavity. Since higher pump power will destroy the

MWCNT-PVA SA due to the thermal characteristic of the MWCNT, the applied pump power was controlled below 133.8 mW.

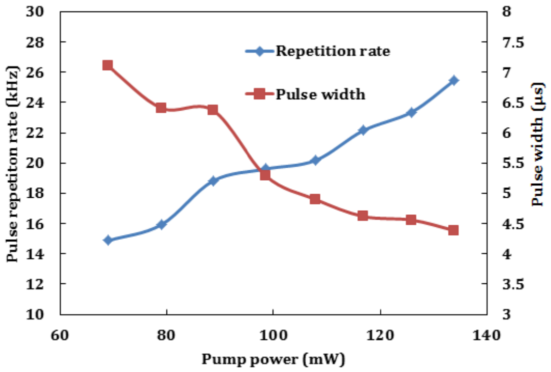

Fig. 7 Repetition rate and pulse width of the proposed multi-wavelength Q-switched EDFL against the pump power

Fig. 8 shows how the average output power and pulse energy of the multi-wavelength Q-switched EDFL are related with the pump power. As shown in the figure, average output power almost linearly increased from 11.0 µW to 13.9 µW as the pump power increases from 69.0mW to 133.8 mW while the pulse energy fluctutating within 0.54 nJ to 0.74 nJ at the same pump power range. These results show that the MWCNTs-PVA SA functions very well as a typical saturable absorber to achieve the Q-switching. On the other hand, the highly nonlinearity of PCF had induced NPR to achieve multi-wavelength. This is proved since we only observed an unstable multi-wavelength laser with continuous wave operation when the MWCNTs-PVA SA is removed from the set-up as shown in Fig. 9. It is also observed that the incorporation of SA improves the stability of the multi-wavelength lasing due to the nonlinearity of MWCNT that had induced the four wave mixing (FWM).

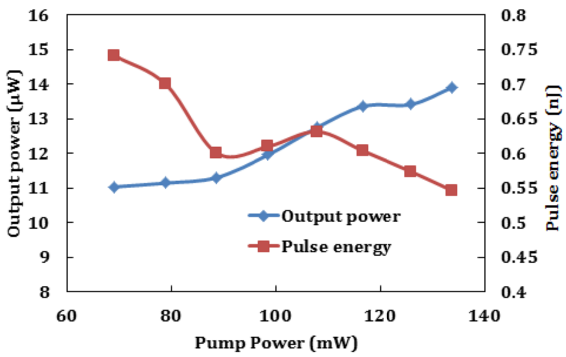

Fig. 8 Output power and pulse energy of the proposed multi-wavelength Q-switched EDFL against the pump power

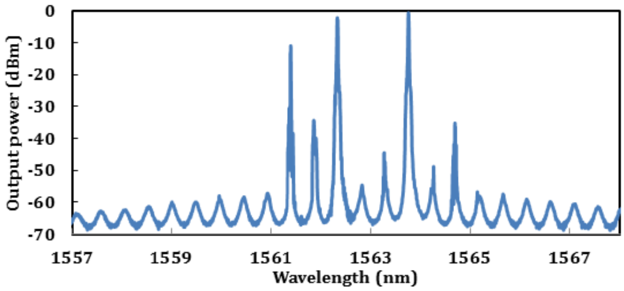

Fig. 9 Output spectrum of the proposed ring EDFL when SA excluded from laser cavity

IV. Conclusion

A simple multi-wavelength Q-switched EDFL is proposed and demonstrated based on 50 m long PCF and MWCNTs-PVA SA. The EDFL generates a stable multi-wavelength laser with spacing of 0.48 nm and Q-switching pulse at a threshold pump power as small as 69.0 mW. By varying the pump power from threshold power to maximum 133.8mW, pulse repetition rates can be increased from 14.9 kHz to 25.4 kHz, whereas the pulse width reduces from 7.1 µs to 4.4 µs. The maximum pulse energy of 0.74 nJ is obtained at pump power of 69.0 mW.

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