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Abstract. Due to an enormous potential of pulsed lasers in applications such as manufacturing, metrology, environmental sensing, and biomedical diagnostics, a high-power and stable Q-switched erbium-ytterbium codoped double-clad fiber laser (EYDFL) incorporating of multiwall carbon nanotubes (MWCNTs) saturable absorber (SA) made based on polyvinyl alcohol (PVA) with a 3:2 ratio is demonstrated. The SA was fabricated by mixing a dilute PVA solution with an MWCNTs homogeneous solution. Subsequently, the mixture was sonicated and centrifuged to produce a homogeneous suspension that was left to dry at room temperature to form the MWCNTs-PVA film. The SA was formed by inserting the film between a pair of FC/PC fiber connectors. Then, it was integrated into the EYDFL’s ring cavity, which uses a 5-m-long erbium-ytterbium codoped fiber (EYDF). The lasing threshold for the Q-switched EYDFL was at 330 mW. At the maximum available pump power of 900 mW, the proposed EYDFL produced Q-switched pulses with a repetition rate of 74.85 kHz, pulsewidth of ∼3.6 μs, and an average output power of about 5 mW. The maximum energy per pulse of ∼85 nJ was obtained at pump power of ∼700 mW with peak power of 21 mW. © 2016 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.OE.55.10.106112]

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1 Introduction

Of late, pulsed laser has surged in popularity as an interesting topic in the areas of basic research, communications, medicine, remote sensing, range finding, material processing, and manufacturing.1–4 This is due to its ability to direct its energy content into repeatable envelopes at a constant rate to produce a higher peak power beam as compared to the continuous wave (CW) laser. In telecommunication, the high-energy pulses will allow the data to be transmitted for a longer distance. Meanwhile, these repetitive high-energy pulses can be used for cutting in manufacturing and material processing with a high precision.

Short pulses with high-energy content at a relatively low repetition rate are achievable using Q-switching techniques that attenuate the lasing feedback inside the cavity. Q-switched fiber laser can be constructed either using active and passive techniques.5,6 However, due to their simplicity, compactness, and versatile design, passively Q-switched lasers are preferred over the active techniques that are normally bulky.

There are two types of saturable absorbers (SA) commonly used in passive Q-switched pulsed lasers, transition metal-doped crystals,6 and semiconductor saturable absorber mirrors.7 However, fabricating these SAs are complex and costly. In addition, they are not compatible with many optical fibers.

Since the discovery of graphene in 2014, there has been tremendous growth in research works involving two-dimensional materials. Similarly in pulsed laser generation, many works have been reported in the applications of different types of SA to generate pulses. Apart from carbon-based SA, such as CNTs and graphene,8 there are also research interests in topological insulator (TI),9 transition metal dichalcogenide (TMDCs),10 and the new black phosphorus (BP).11 While the TI, TMDC, and BP materials have an improved energy band-gap where they normally have direct band-gap as compared to CNTs (SW- and MW-), the absorption wavelength of CNTs is better that that of the aforementioned materials. Graphene, on the other hand, do not have a suitable energy band-gap that makes the photon absorption and the saturation difficult to occur.

In the last few years, single-walled carbon nanotube (SWCNT) material has been tested as an SA in fiber lasers that show fast recovery time, broad spectral range in the near-infrared, and chemical stability.12–18 These attributes are suitable for low power pulses since its thin layer structure can resist low optical power.

One drawback that impedes the widespread use of SWCNT is the special and complex techniques to prepare the raw material that are time consuming. In addition, it also requires a delicate fabrication process, such as the need for nanocatalyst to be grown. Also, since it is made of a thin cylindrical carbon layer, its atomic structure might not be able to sustain high power laser operation.
On the contrary, the preparation of multiple-walled carbon nanotubes (MWCNTs) is cheaper. The MWCNTs can be easily grown on layers of nanoparticles without strict control of other growth conditions. Furthermore, MWCNT is more physically robust than the SWCNT and graphene because of its multiple-walled structure, which is in the form of a stack of concentrically rolled graphene sheets. Due to this structure, the inner walls are protected by the outer walls from damage or oxidation, which results in a higher thermal or laser damage threshold. Therefore, MWCNT could sustain higher heat that suits well for high power pulsed laser generation. As a drawback, since its carbon layer is thick, the light that propagates through could have difficulties in achieving saturation that will limit the generation of the laser pulses. To the best of our knowledge, only a few applications of lasers using MWCNTs materials as SAs have been reported. For instance, mode-locked Nd:YVO4 laser and Q-switched Nd:YAG were demonstrated employing MWCNTs SA in Refs. 21 and 22, respectively.

In this paper, a stable passively Q-switched erbium-ytterbium codoped fiber laser (EYDFL) operating at 1550 nm region is demonstrated using a low-cost MWCNTs film-based SA, which is prepared using polyvinyl alcohol (PVA) as a host polymer. A 5-m-long double-clad erbium-ytterbium codoped fiber (EYDF) is used as the gain medium in the ring cavity laser and the SA is integrated in the cavity by sandwiching the MWCNTs-PVA SA thin film between two fiber connectors, with a low Q-switching threshold of 330 mW is observed.

2 Preparation of Multiwall Carbon Nanotubes Saturable Absorber

The fabrication of SA incorporating dispersed MWCNTs film is the key part of Q-switching generation. To match the EYFL operating at 1550 nm, we used MWCNTs with a distributed diameter of 10 to 20 nm, length of 1 to 2 μm, and purity of 99%. Initially, the water-solvent property of MWCNTs is improved using functionalization technique. The functionalizer solution was prepared by dissolving 4 g of sodium dodecyl sulfate (SDS) in 400-ml deionized water. It has average molecular weight of 288.38 g/mol. SDS has the ability of dispersing the carbon nanotubes because it possesses good dispersing stability in the water. Then, 250 mg of MWCNT powder was poured into the solution, and the mixture was sonicated for 60 min at 50 W to obtain the homogeneous dispersion of MWCNTs. The solution was further centrifuged at 1000 rpm to remove large particles of undispersed MWCNTs from the suspension.

PVA with monomer formula C₆H₄O was chosen as the host material, as it is a water-soluble synthetic polymer. Furthermore, it has excellent adhesive, emulsifying, and film forming properties. It also has high tensile strength, flexibility, and high oxygen. The PVA solution was prepared by dissolving 1 g of PVA in 400-ml distilled water. Then, the PVA solution was mixed with the earlier MWCNTs solution in 3:2 ratio to form the precursor after the mixture was stirred using an ultrasonic cleaner for about 1 h. By then the precursor should have enough viscosity to form the MWCNTs-PVA film. Finally, a small amount of precursor was spread thinly on the glass substrate, and left to dry at room temperature for about 1 week to form the SA thin film with a thickness around 50 μm.

To implement MWCNTs-PVA film into the laser cavity to function as an SA, the earlier prepared SA film was cut into small square pieces. The size of each piece of the SA was around 2 × 2 mm² as shown in Fig. 1. Then, the SA was sandwiched between two FC/PC fiber connectors, after depositing index matching gel onto the fiber ends to reduce the Fresnel reflection on the surface of the material. It is integrated in the laser cavity for the Q-switching operation. The insertion loss of the SA was ∼3.0 dB at 1550 nm.

Figure 2 shows the experimental setup of the proposed Q-switched EYDFL using the fabricated MWCNTs-PVA film as an SA. A 5-m-long all-silica double-clad EYDF is used as the gain medium. The EYDF has absorption coefficient of 18.7 dBm−1 at 1550 nm. By codoping erbium with ytterbium, the extractable output power can be increased significantly by improving pump absorption near 915 and 975 nm. The EYDFL is also weakly affected by the concentration quenching phenomenon and does not exhibit the exited-state absorption that usually reduces the pump efficiency. These attributes allow compact, high efficiency, high reliability, and high power laser at 1550 nm being generated by using this codoped fiber together with cladding-pumped laser.

However, for cladding pumping, the absorption of erbium is impractically low. Therefore, in comparison to widely used erbium-doped fiber laser, ytterbium is added to absorb the pump power by enabling the pump energy to be transferred nonradiatively from Yb3+ -ions to Er3+ -ions, which then emits at around 1550 nm. The fiber is pumped by a 974-nm multimode laser diode. The pump source is injected into the fiber via a multimode
combiner (MMC) to generate an amplified spontaneous emission (ASE) in 1550 nm region. An optical isolator is placed in between the MMC and output coupler to ensure unidirectional laser oscillation within the cavity. A 95:5 coupler is used to tap 5% of the oscillating signal from the cavity for spectral and temporal analysis. The remaining signal is allowed to oscillate and interacts with the MWCNTs SA in the ring cavity to generate a Q-switching pulse operating within the ASE region. The total length of the cavity is approximately around 18.6 m. The extracted laser output of the 95/5 coupler is split further by a 3-dB coupler into two equal portions and directed into an optical spectrum analyzer (OSA) and a photodetector for spectral and temporal analysis (via oscilloscope), respectively.

3 Results and Discussion

Raman spectroscopy is used to confirm the presence of MWCNTs inside the polymer film. Figure 3 shows the Raman spectrum obtained from the spectroscopy, which obviously indicates a well-defined peaks of G and G' bands at 1580 and 2705 cm\(^{-1}\), which are the features of the MWCNTs. We also see a prominent D band at around 1350 cm\(^{-1}\), which indicates the presence of some disorders to the carbon structure.\(^1\) This indicates that the carbon nanotubes are of a multiwalled type, which has multilayer configuration and disorder structure. Other distinguishable features like G + B band (2920 cm\(^{-1}\)), a small peak at 854 cm\(^{-1}\) and Si are also observed in the spectrum. Inset of Fig. 3 shows the transmission spectrum of the film, which was obtained by using an UV-vis/NIR spectrophotometer. The transmission spectrum has a direct relationship with the absorption according to the following equation:

Transmission (%) = 100% – Absorption (%). (1)

In this case, the spectrum indicates that the initial transmission at 1550 nm is around 46%. Therefore, according to Eq. (1), the absorption at this wavelength was measured as 54%.

After Raman spectroscopy test, the fabricated SA is integrated in the optical cavity. The cladding pump power of the 974-nm pump laser is incrementally adjusted and the output is observed. At the pump power of \(\sim 330\) mW, the first appearance of Q-switch operation is observed. This is the threshold value of the pump power that produces Q-switching effect. At this threshold pump power, the laser yields Q-switching operation with a repetition rate of 16.45 kHz. As the pump power is increased to a maximum value of \(\sim 900\) mW, higher pulse rate of 74.85 kHz is observed.

However, the pulse width decreases as the pump power increases. At \(\sim 330\) mW, a wide pulse width of \(\sim 8.8\) \(\mu\)s is obtained as compared to a narrower pulse width of \(\sim 3.6\) \(\mu\)s at the maximum pump power. Meanwhile, the pump power of \(\sim 600\) mW yields a repetition rate and pulse width of \(\sim 44.33\) kHz and \(\sim 4.9\) \(\mu\)s, respectively. Different repetition rates and pulse widths generated by the Q-switched laser at different pump powers are shown in Fig. 4.

Figure 5 summarizes the relations between repetition rate and pulse width against pump power of the Q-switched laser. It is observed that the repetition rate is almost linearly related with the pump power. A higher repetition rate is expected if a more powerful pump source is used. Over time, at a fixed pump power, the repetition rate of the pulses is unchanged. This indicates that the system is stable and the MWCNT-based SA can sustain Q-switching operation at higher pump powers. Conversely, the pulse width of the system decreases as the pump power increases, as expected of a Q-switched laser operation. At the threshold pump power of \(\sim 330\) mW, a pulse width of \(\sim 8.8\) \(\mu\)s is observed but it decreases quickly to \(\sim 6.3\) \(\mu\)s with an increase of power to \(\sim 530\) mW. However, subsequent increase in pump power only decreases the pulse width at a slower rate until it reaches its minimum value of 3.6 \(\mu\)s at \(\sim 900\) mW.

Figure 6 shows an almost linear relationship between the average output power and the pump power. The maximum average output power of 5.5 mW is obtained at the pump power of \(\sim 800\) mW. At pump power below \(\sim 300\) mW, the laser operates in the CW mode before it commences the Q-switched operation with an average output power of 0.1 mW at the threshold pump power of 330 mW.

The pulse energy and peak power of the generated pulses as a function of pump power are shown in Fig. 7. It is observed that the pulse energy increases from 10 to 85 nJ as the pump power increases from 330 to 700 mW. However, as the pump power exceeds 700 to 900 mW, the pulse energy slightly drops to 67 nJ. The peak power of the pulses also shows a similar pattern, increasing from 1 to 21 mW as the pump power is raised from 330 to \(\sim 700\) mW before dropping to 19 mW at 900 mW. This effect is due to the system going past its optimal operating point at 700 mW. There is a possibility that above a certain intracavity power level, other nonlinear effects may take place, resulting in more average loss and, thus, a decrease in the performance of the system. It is also possible that, at this point, the outer layer may suffer a slight damage. However, due to the availability of multiple layers of CNTs in the SA, it can be surmised that the remaining layers are still able to sustain high power laser operation. When the above measurements were repeated, similar results were obtained, indicating that the SA can still sustain a high power laser operation.

The threshold for possible damage of the MWCNT, taking into account at peak power of 21 mW with a mode field diameter or core size of 125 \(\mu\)m, results into a power
intensity of 1.71 MW/m². The result obtained by this codoped fiber material achieved significantly higher power as compared to the results published earlier in Refs. 3, 4, and 30. The repetition rate nearly tripled and the output power increased by a factor of 1000. This is achieved at higher pump power.

Throughout the experiment, the pump power had been increased up to 900 mW. This corresponds nearly as much as 2 A of current of the high power laser diode. Even after the laser had been switched on for over an hour at this power level, there were no deviations in the pulse amplitude observed. Hence, at this operating power the MWCNT thin-film did not suffer from optical damage.
power up to only 900 mW. However, further increase in power was not possible as our in-house built high power laser diode has a limited operation switching threshold occurred at 0.33 W. The optical spectra of the Q-switched EYDFL output are shown in Fig. 8. In the figure, the output spectra of the Q-switched EYDFL are obtained from the OSA at pump powers of ∼330, ∼600, and ∼900 mW. The output power is as high as −3 dBm at pump power of 900 mW and −7 dBm at 600 mW. The results were measured at wavelength of 1545 nm. The high signal-to-noise ratio shows that the Q-switched operation is stable. From the results, it can be seen that MWCNTs-PVA can provide a good alternative as an SA in producing stable Q-switched pulses since the fabrication is cheap and simple. The multi-wall structure can sustain higher average output power using codoped configuration as compared to previous results using SWCNTs and MWCNTs, which the input power has also increased for higher power operation.

It is noted that throughout the experiment, no mode-locking behavior was observed. This is possibly due to the fact that our cavity could not saturate the pulse fast enough. Although the additional single mode fiber had been used to control the dispersion of the propagation modes, the mode-locking effect still did not appear.

4 Conclusions

A passively Q-switched EYDFL using MWCNTs-PVA film as an SA targeting for medium to high power applications is demonstrated. The MWCNTs-PVA SA was fabricated by mixing suspended MWCNTs with a PVA solution and left to dry at room temperature to form the SA film. The film is positioned between two fiber ferrules. Then, the SA is integrated into the laser cavity that uses a 5-m double-clad EYDFP as the gain medium. The SA absorbed and released the lasing light at a constant interval to generate Q-switched pulses at 1545 nm at the pumping threshold of ∼330 mW. At pumping power of ∼700 mW, the laser operates at a frequency of 53.42 kHz and a pulse width of 4.14 μs. The energy per pulse and peak power values are 85 nJ and 21 mW, respectively. By varying the 980-nm pump power from 330 to 900 mW, the repetition rate of the EYDFL increases from 18 to 72 kHz. At the maximum input pump power of 900 mW, an average output power of 5 mW is obtained. The output of the Q-switched is stable and higher than that of a similar system using SWCNTs-PVA SA.

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References


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