Q-switched Brillouin fibre laser with multi-wall carbon nanotube saturable absorber

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Abstract: A Q-switched Brillouin fibre laser (BFL) is successfully demonstrated using multi-walled carbon nanotubes (MWCNTs) embedded in polyvinyl alcohol (PVA) film as a passive saturable absorber (SA) for the first time. The SA is obtained by sandwiching the developed MWCNTs–PVA film between two FC/PC fibre connectors after depositing index-matching gel onto the fibre ends. The proposed Q-switched BFL incorporates a 5 km long dispersion shifted fibre in a ring cavity structure to generate Stokes shifted by 0.08 nm from the Brillouin pump wavelength. The BFL starts to generate a Q-switching pulse train at threshold pump power of 5 dBm. As the BP power is varied from 5.0 to 6.0 dBm, the repetition rate of the Q-switched BFL exhibits an increasing trend from 27.75 to 30.21 kHz, whereas the pulse width exhibits a decreasing trend from 3.25 µs to 1.11 µs. The maximum pulse energy of 0.13 nJ is obtained at maximum BP power of 6.0 dBm.

1 Introduction

Q-switched fibre lasers are mainly used for generating high energy pulses at relatively low repetition rates. They can be constructed by active or passive techniques. Compared with those fabricated using the active technique, passively Q-switched fibre lasers are advantageous in compactness, simplicity and flexibility in design [1]. They have been intensively investigated using different kinds of saturable absorbers (SAs) such as transition metal-doped crystals and semi-conductor saturable absorber mirrors [2, 3]. However, these SAs are complex and expensive to fabricate. Furthermore, they are incompatible with many optical fibres which limits widespread application. In the past few years, single-walled carbon nanotubes (SWCNTs) have been discovered to have promising potential in mode locked fibre laser systems because of their intrinsic saturable absorption properties, ultrafast recovery time and wide absorption wavelength bandwidth [4, 5].

Recently, new, multi-walled carbon nanotubes (MWCNTs) [6, 7] have also attracted much attention because they possess many advantages in non-linear optics. The growth of the MWCNT material does not need complicated techniques or special growing conditions so that its production yield is high for each growth. Therefore, the production cost of MWCNT material is about 50%–20% of that of SWCNT material [8]. In addition, MWCNT material has good thermal characteristics, which is of great importance for high power ultrafast laser development. Compared with SWCNTs, the MWCNTs have higher mechanical strength, better thermal stability as well as the ability to absorb more photons per nanotube because of its higher mass density of the multi-walls. These favourable features are because of 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 MWCNTs is higher than that of SWCNTs [9, 10]. However, there are reported that the MWCNTs has a high saturation intensity and thus it was considered a not good SA for mode-locking operation as this would require high irradiation intensity to reach absorption saturation [11, 12]. Therefore to date, there are only a few reported works on application of MWCNTs material as a SA. For instance, Lin *et al.* [13] employ multi-walled MWCNTs based SA for mode locking of a Nd:YVO_4 laser. In another work, Q-switched Nd-YAG laser is demonstrated using the MWCNTs based SA as a Q-switcher [14].

On the other hand, many works have also been reported on Brillouin fibre lasers (BFL), which use a non-linear effect in optical fibre to generate a narrow linewidth and high coherence laser [15, 16]. The applications of such a laser include optical gyroscope, microwave frequency generation, high-rate amplitude modulation, interferometric position sensors and laser radar. In this paper, a Q-switched BFL using a passive SA made of MWCNTs embedded in a polyvinyl alcohol (PVA) film is demonstrated for the first time. It exploits the stimulated Brillouing scattering (SBS) effect from the interaction between intense pump light and acoustic waves in a 5 km long dispersion shifted fibre (DSF) to generate a non-linear laser shifted by 0.08 nm from the pump wavelength. The SA is constructed by sandwiching a MWCNTs-PVA film between two fibre connectors. The laser delivers Q-switched pulses with a repetition rate of 30.21 kHz and pulse width of 1.11 µs at the pump power of 6 dBm.

2 Experimental arrangement

The MWCNTs material used for the fabrication of the absorber in this experiment was dispersed in water with the assistance of a surfactant. The diameter of the MWCNTs used was about 10–20 nm and their length was around 1 to 2 µm. The surfactant solution was prepared by dissolving 4 g of sodium dodecyl sulphate in 400 ml deionised water. Then 250 mg of MWCNT was added to the solution and the homogenous dispersion of MWCNTs was achieved after the mixed solution was sonicated for 60 min at 50 W. The solution was then centrifuged at 1000 rpm to remove large particles of undispersed MWCNTs to obtain a stable dispersed suspension. Next, PVA solution was prepared by dissolving 1 g of PVA in 120 ml of deionised water. Afterward, the dispersed MWCNTs suspension was poured into the PVA solution at four to one ratio to obtain MWCNTs-PVA composite. The MWCNTs-PVA composite was made homogeneous by sonification process for more than one hour. It was then casted onto a glass petri dish and left to dry at room temperature for about one week to produce thin film with thickness around 50 µm. The SA is fabricated by cutting a small part of the prepared film and sandwiching it between two FC/PC fibre connectors, after depositing index-matching gel onto the fibre ends. The insertion loss of the SA was measured to be around 3 dB at 1550 nm.

The experimental set-up of the proposed BFL is illustrated in Fig. 1, which consists of a Brillouin pump (BP), a 3-port optical circulator, a 5 km DSF, a 80:20 coupler and a MWCNTs-PVA SA. The BP is an external tunable laser source with a maximum power of 6 dBm at 1550 nm wavelength. The BP is launched into the DSF from ports 1 to 2 of the optical circulator to generate the backward propagating Stokes via the SBS process. The Stokes oscillates inside the ring cavity to initiate laser at a wavelength which is downshifted by 0.08 nm from the BP wavelength. The MWCNTs-PVA SA is used to generate a Q-switching pulse train. The output of the laser is collected from the cavity via a 80:20 coupler which retains 80% of the light in the ring cavity to oscillate. The optical spectrum analyser (Yokogawa, AQ6370B) is used for the spectral analysis of the BFL's wavelength with a spectral resolution of 0.02 nm. The temporal characteristic of the laser is measured by a photo-detector and an oscilloscope.

To check the existence of the MWCNTs in the film, we use the field emission scanning electron microscope (FESEM) and Raman spectrometer to check the image and its material characteristic, respectively. Fig. 2 illustrates the FESEM image of the film at magnification of 35,000 times which indicates the MWCNTs are randomly embedded in the polymer composite. Fig. 3 shows the Raman spectrum, which is dominated by two peaks: the *G* band at 1593 cm^{-1}, which corresponds to tangential stretching C-C vibrations in the nanotube wall plane and the D-band at 1356 cm^{-1}, which originates from a double resonance process and is because of the presence of amorphous disordered carbon. In the SWCNT, there is a series of bands appearing at the frequency region of around 200 cm^{-1} known as radial breathing mode (RBM) bands. The RBM bands correspond to the expansion and contraction of the tubes. The RBM modes are not presented in the MWCNT because the outer tubes restrict the breathing mode. The *G*′ band is also observed at 2720 cm^{-1} because of two-phonon scattering phenomena. In addition, another intense peak at 2915 cm^{-1} is also obtained because of the existence of PVA polymer. We also use the UV-vis/NIR spectrophotometer to check the transmission spectrum of the film at 1550 nm wavelength region. The initial transmission at 1550 nm is measured to be around

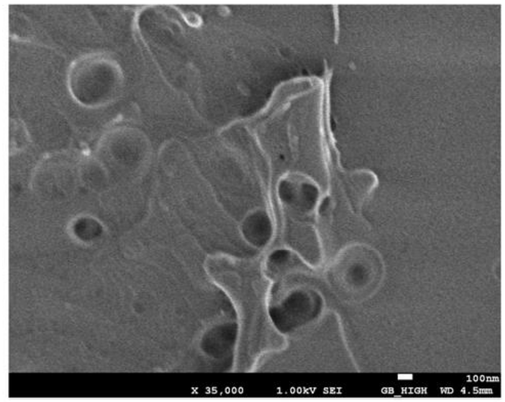

Fig. 2 *FESEM image of the prepared MWCNTs-PVA film*

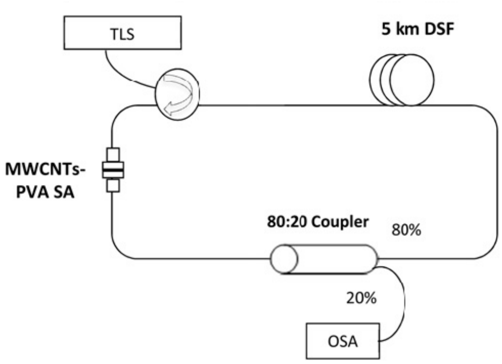

Fig. 1 *Schematic configuration of the proposed Q-switched BFL*

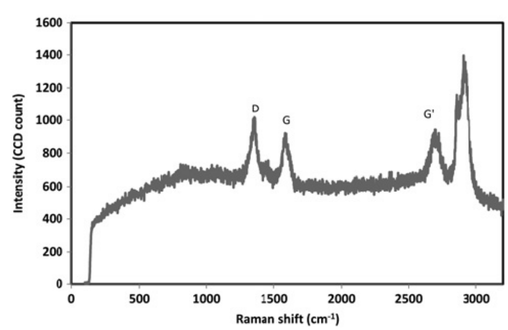

Fig. 3 *Raman spectrum obtained from the MWCNTs-PVA film*

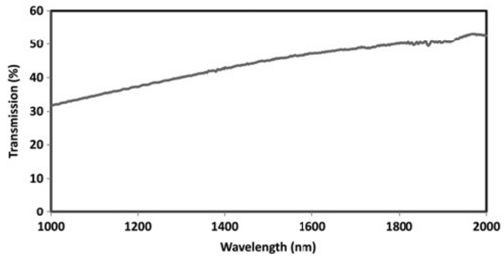

Fig. 4 *Transmission spectrum of the MWCNTs-PVA film*

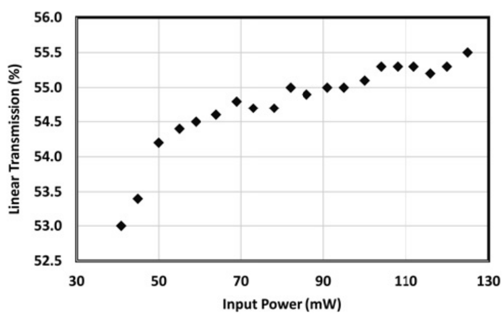

Fig. 5 *Linear transmission curve of the MWCNTs-PVA film, which shows that the saturable absorption and non-saturable absorption of around 4% and 45%, respectively*

46% as shown in Fig. 4. The dependence of the linear transmission of the MWCNTs-PVA film on the signal power is also investigated as shown in Fig. 5. In the experiment, the input signal wavelength is fixed at 1550 nm. The curve indicates that the film has saturable absorption (modulation depth) of around 4% and non-saturable absorption of around 45%.

3 Results and discussion

Fig. 6 shows the output spectrum of the Q-switched BFL at different pump power. The Brillouin Stokes operates at a wavelength which is 0.08 nm shifted from the BP wavelength at BP power of 4.5 dBm. By increasing the BP power to 5 dBm, the peak power of the Stokes increases drastically from −49.4 to −15.5 dBm. The peak power linearly increases to −9.8 dBm as the pump power further increases to 6 dBm. As shown in Fig. 6, anti-Stokes is also obtained at a wavelength, which is 0.08 nm shorter than the BP. The regenerative FWM between co-propagating Rayleigh-backscattered pump and Brillouin Stokes waves can generate an idler wave or anti-Stokes at the wavelength 0.08 nm shorter than the pump. However, the power of the idler should be proportional to the pump power squared times the Stokes power. Another idler is also expected to appear at a wavelength 0.08 nm longer than the Stokes wave because of the FWM interaction. Since the anti-Stokes power is almost unchanged with the pump power and another idler cannot be found in Fig. 6, we expect that the origin of the anti-Stokes component may be spontaneous anti-Stokes Brillouin scattering. The plot of the peak power against the BP power is shown in Fig. 7 for both BFLs configured with and without the SA. Without the MWCNTs-PVA SA, the BFL threshold is observed to be around 1 dBm. As the SA is incorporated in the cavity, the cavity loss is increased and the Brillouin laser threshold increases to around 5 dBm. After reaching the threshold, the peak power of the BFL linearly increases with the pump power. The average output power is lower in the Q-switched BFL because of the SA insertion loss.

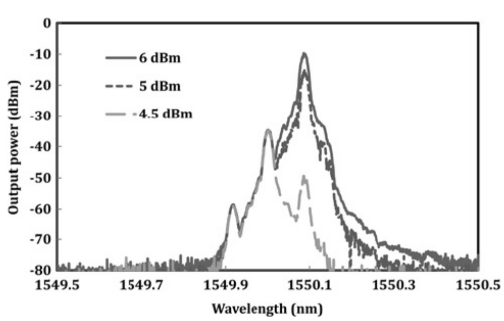

Fig. 6 *Output spectrum of the proposed Q-switched BFL with MWCNTs-PVA SA*

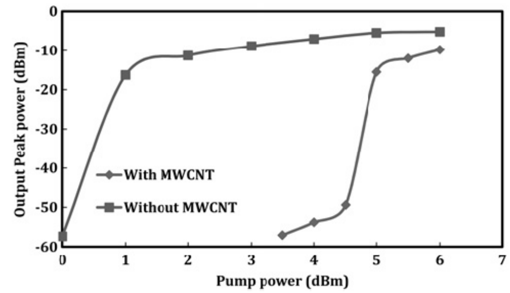

Fig. 7 *Output peak power of the BFL against the BP power with and without the MWCNTs-PVA SA in the laser cavity*

Fig. 8 shows the typical oscilloscope trace of the BFL configured without the SA at two different BP powers of 1 and 5 dBm. At threshold pump power of 1 dBm, a random pulse is obtained because of a non-linear

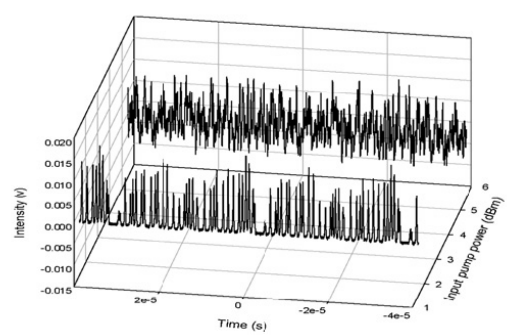

Fig. 8 *Typical oscilloscope trace from the BFL configured without the SA at two different BP powers; 1.0 and 5.0 dBm*

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