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Passively Q-switched fiber lasers using a multi-walled carbon nanotube polymer composite based saturable absorber

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ABSTRACT

We demonstrate a simple, compact and low cost Q-switched fiber lasers based on Erbium-doped fiber (EDF) and Thulium-doped fiber (TDF) to operate at 1534.5 nm and 1846.4 nm, respectively by exploiting a multi-walled carbon nanotubes (MWCNTs) polymer composite film based saturable absorber (SA). The composite is prepared by mixing the MWCNTs homogeneous solution into a dilute polyvinyl alcohol polymer solution before it is left to dry at room temperature to produce thin film. Then the film is sandwiched between two FC/PC fiber connectors and integrated into the laser cavity for Q-switching pulse generation. The EDF laser generates a stable pulse train with repetition rates ranging from 38.11 kHz to 48.22 kHz by varying the 980 nm pump power from 39.0 mW to 65.3 mW. At the 65.3 mW pump power, the pulse width and pulse energy were 5.3 μs and 99.75 nJ, respectively. The TDF laser generates a stable pulse train with 10.38 kHz repetition rate, 17.52 μs pulse width and 11.34 nJ pulse energy at 121.1 mW 800 nm pump power. A higher performance Q switching is expected to be achieved in both fiber lasers with the optimization of the SA and laser cavity.

1. Introduction

Q-switched fiber lasers have gained a tremendous research interest in recent years for their potential applications in optical communication, fiber sensor, laser processing, laser marking, etc. Compared with the actively Q-switched ones, passively Q-switched lasers have attracted much attention due to their advantages of compactness, low cost, flexibility and simplicity of design. Different kinds of saturable absorbers (SAs), such as the transition metal-doped crystals [1] and semiconductor quantum-well structures [2], have been applied to realize Q-switched fiber lasers especially for operation in 1550 nm region. 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. Over the last few years, the use of single-walled carbon nanotubes (CNT) material as a saturable absorber (SA) has been widely investigated in Q-switched fiber lasers in both 1550 nm and 1900 nm regions [3–6]. 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, a new member of CNT family, multi-walled carbon nanotubes (MWCNTs) [7,8] have also attracted many attentions because they possesses many advantages in nonlinear 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 single-walled CNT material [9].

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Additionally, MWCNT material has good thermal characteristics, which is of great importance for high power ultrafast laser development. The Young modulus of MWCNT is around 1000 GPa [10] and the thermal conductivity of MWCNT, 3000 Wm K, is very high [11]. Compared with SWCNTs, the MWCNTs have higher mechanical strength, better thermal stability as well as can absorb more photons per nanotube due to its higher mass density of the multi-walls [9]. These favorable 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 single-walled CNTs [12,13].

To date, there are only a few reported works on application of MWCNTs material as a saturable absorber. For instance, Lin et al. [14] employs multi-walled MWCNTs based saturable absorber for mode locking of a Nd:YVO_4 laser. In another work, Q-switched Nd–YAG laser is demonstrated using the MWCNTs based saturable absorber as a Q-switcher [15]. In this paper, Q-switched fiber laser is demonstrated using a new developed MWCNTs-based SA. To the best of our knowledge, this is the first demonstration using MWCNTs as the Q-switcher in the all-fiber fiber laser. The SA is constructed by sandwiching a multi-walled CNT-polyvinyl alcohol (MWCNT-PVA) film between two fiber connectors. The performance of the Q-switched is investigated for two different gain media; Erbium-doped fiber (EDF) and Thulium-doped fiber (TDF).

2. Preparation and Raman characterisation of the saturable absorber

At first, the MWCNTs material used for the fabrication of the absorber in this experiment is functionalized so that it can be dissolved in water. The diameter of the MWCNTs used is about 10–20 nm and the length distribution is from 1 to 2 μm. The functionalizer solution was prepared by disolving 4 g of sodium dodecyl sulphate (SDS) in 400 ml deionized water. 250 mg 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 dispersed suspension that is stable for weeks. MWCNTs-PVA composite was prepared by adding the dispersed MWCNTs suspension into a PVA solution by three to two ratio. PVA solution was prepared by dissolving 1 g of PVA ($M_w = 89 \times 10^3$ g/mol) in 120 ml of deionized water. The homogeneous MWCNTs-PVA composite was obtained by sonification process for more than 1 h. The CNT-PVA composite was casted onto a glass petri dish and left to dry at room temperature for about one week to produce thin film with thickness around 10 μm. The SA is fabricated by cutting a small part of the prepared film (2×2 mm^2) and sandwiching it between two FC/PC fiber connectors, after depositing index-matching gel onto the fiber ends. The insertion loss of the SA is measured to be around 3 dB at 1550 nm.

Raman spectroscopy was performed on the MWCNT-PVA film using laser excitation at 532 nm to confirm the presence of MWCNT. Fig. 1 shows the Raman spectrum, where obviously indicates the distinct feature of the MWCNT. It is shown that the Raman spectrum bears a lot of similarity to graphene, which is not too surprising as it is simply a rolled up sheet of graphene. MWCNT has many layers of graphene wrapped around the core tube. We can see well defined G (1580 cm^{-1}) and G′ (2705 cm^{-1}) bands in the figure as there were in graphene and graphite. The G band originates from in-plane tangential stretching of the carbon–carbon bonds in graphene sheet. We also see a prominent band around 1350 cm^{-1}, which is known as the D band. The D band originates from a hybridized vibrational mode associated with graphene edges and it indicates the presence of some disorder to the graphene structure. This band is often referred to as the disorder band or the defect band and its intensity relative to that of the G band is often used as a measure of the quality with nanotubes. There is another series of bands appearing at the low frequency end of the spectrum known as Radial Breathing Mode or RBM bands. The RBM bands correspond to the expansion and contraction of the tubes. The RBM modes are not clearly present in the MWCNT because the outer tubes restrict the breathing mode. As expected, the prominent D band is observed in Fig. 1, which indicates that the carbon nanotubes are a multi-walled type, which has multi-layer configuration and disorder structure. The D′ band which is a weak shoulder of the G-band is also observed at 1613 cm^{-1} due to double resonance feature induced by disorder and defect. 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. The nonlinear characteristic of the MWCNT was also investigated where we measured the modulation depth at around 4.7%.

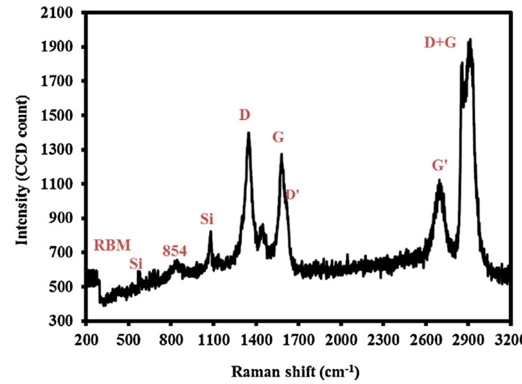

Fig. 1. Raman spectrum obtained from the MWCNT-PVA film.

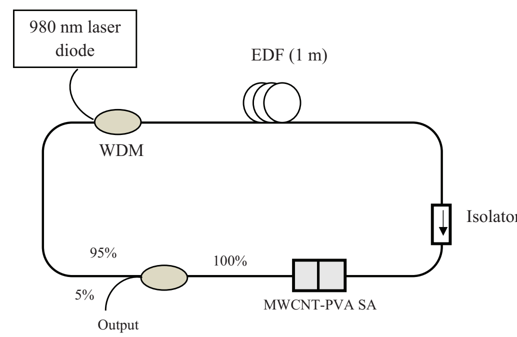

Fig. 2. Schematic configuration of the Q-switched EDFL.

3. Q-switched Erbium-doped fiber laser operating at 1534.5 nm region

The schematic of the experimental setup of the passively Q-switched Erbium-doped fiber laser (EDFL) is shown in Fig. 2. It consists of a 1 m long EDF, a 980/1550 nm wavelength division multiplexer (WDM), an isolator, a newly developed MWCNT-PVA based SA, and 95/5 output coupler in a ring configuration. The EDF used has a core and cladding diameters of 4 μm and 125 μm, respectively, a numerical aperture of 0.16 and Erbium ion absorption of 23 dB/m at 980 nm. It is pumped by a 980 nm laser diode via the WDM. An isolator is incorporated in the laser cavity to ensure unidirectional propagation of the oscillating laser. The output of the laser is tapped from the cavity through a 95/5 coupler while keeping 95% of the light to oscillate in the ring cavity. The optical spectrum