Optics and Laser Technology 105 (2018) 129–134

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

Stable multi-wavelength erbium-doped fiber laser assisted by graphene/PMMA thin film

K.Y. Lau [a], M.H. Abu Bakar [a], A.R. Md Zain [b], A.F. Abas [c], M.T. Alresheedi [c], M.A. Mahdi [a,*]

[a] Wireless and Photonic Networks Research Centre, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia
[b] Institute of Microengineering and Nanoelectronics (IMEN), Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
[c] Department of Electrical Engineering, College of Engineering, P.O. Box 800, King Saud University, Riyadh 11421, Saudi Arabia

ARTICLE INFO

Article history:
Received 18 September 2017
Received in revised form 19 January 2018
Accepted 1 March 2018

Keywords:
Fiber laser
Multi-wavelength
Erbium
Graphene

ABSTRACT

Multi-wavelength erbium-doped fiber laser (EDFL) is of significant interest due to its operation within the conventional optical communication band. The primary concern in multi-wavelength EDFL is the low stability of its gain medium in room temperature. This work proposed the use of graphene-polymethyl methacrylate (PMMA) thin film as a stabilizer and nonlinear medium to generate stable multi-wavelength EDFL. Six channels with a constant spacing of 0.62 nm are observed within 10 dB peak power difference. The peak power stability of these lasers is measured at less than 0.8 dB within an observation time of 300 min. These findings validate the potential of graphene/PMMA thin film stabilizer as a key element in producing simple and highly stable multi-wavelength EDFL structure.

1. Introduction

Multi-wavelength fiber laser (MWFL) has evoked substantial research efforts in optoelectronics and photonics applications. Some real-world applications include optical sensor, dense wavelength division multiplexing system, optical communication, optical instrumentation, and signal processing. Erbium-doped fiber (EDF) with its broadband gain in conventional communication windows is widely used as the gain medium for generating simultaneous wavelengths [1]. However, erbium-doped fiber laser (EDFL) is unstable at room temperature due to gain mode competition in EDFs. Various approaches have been proposed to alleviate the gain mode competition in EDFL, including cooling EDF in nitrogen liquid [2], incorporating polarization hole burning effect [3,4], utilizing hybrid gain medium of Brillouin and EDF [5], employing semiconductor optical amplifier with EDF [6], using coupled microfiber Mach-Zehnder interferometer [7], and inducing four-wave mixing effect [8,9]. Apart from these methods, nonlinear polarization rotation (NPR) technique has also been proposed to reduce gain mode competition by inducing intensity and wavelength dependent loss [10]. Long birefringence fiber, such as photonics crystal fiber (PCF) and highly nonlinear fiber (HNLF) are among the media that are commonly used in the induction of NPR-based multi-wavelength laser. For instance, multi-wavelength generation has been demonstrated with intensity-dependent loss of 16.5 km [11] and 20 km single-mode fiber (SMF) [12]. However, long cavity in fiber lasers contributes to high loss that produces inefficient lasing performance.

Therefore, an alternative approach is required to generate multi-wavelength laser in more compact system by incorporating nonlinear materials. For instance, graphene with high nonlinearity mitigates the mode competition in EDF and hence stabilize the multi-wavelength laser [5]. The third-order nonlinear coefficient of graphene is approximately eight orders of magnitude higher than typical glass [13], which enables comparable FWM efficiency for multi-wavelength laser generation to long birefringence fiber [5]. Recently, graphene and molybdenum diselenide ($MoSe_2$) thin films had been proposed to generate stable multi-wavelength EDFLs in Refs. [14] and [15], respectively. In both research works, these 2D materials were utilized as the nonlinear medium and stabilizer for generation of multi-wavelength laser. However, further investigation on multi-wavelength laser performance such as optical-to-signal ratio (OSNR) measurement and output power development were not discussed thoroughly in Refs. [14] and [15]. Additionally, both research works reported the generation of only two dominant multi-wavelength channels within 10 dB peak power difference. This was further compounded by high peak power fluctuations of 3 dB and 5 dB in Refs. [14] and [15], respectively.

In this work, we demonstrate a stable six channel multi-wavelength laser with peak power fluctuation of less than 0.8 dB by employing graphene/polymethyl methacrylate (PMMA) thin film. The material provides high non-linearity to the cavity, and

---

* Corresponding author.
E-mail address: mam@upm.edu.my (M.A. Mahdi).

https://doi.org/10.1016/j.optlastec.2018.03.001
0030-3992/© 2018 Elsevier Ltd. All rights reserved.

the nonlinearly-induced birefringence stabilizes the multi-wavelength laser generation. The high channel count and stability are essential in high frequency response microwave photonics signal processing [16].

2. Characterization of graphene/PMMA device

The graphene/PMMA thin film is obtained from the ACS Material, LLC which has a commercial product name of Trivial Transfer Graphene™. For this product, PMMA is coated on a single layer graphene and this thin film is placed on a polymer substrate. The bare graphene/PMMA thin film is then characterized for its surface roughness and Raman spectrum measurement as shown in Fig. 1(a) and (b), respectively. Based on Fig. 1(a), there are two distinctive colored areas: "blackish" and rainbow-like. The "blackish" region indicates the polymer substrate with non-uniform thickness. On the other hand, the observation of interference-induced rainbow-colored region denotes the graphene/PMMA thin film. The thin film interference is generated by the path difference of the light ray refraction phenomenon at the air-PMMA boundary close to the polymer substrate. The constructive interference condition can be derived by considering the phase differences among the visible light rays introduced at every instance of refraction from a less dense medium to a denser material. Apart from that, the "cloth-like" appearance of the graphene/PMMA thin film is due to the surface structure of the polymer substrate underneath. Fig. 1(b) illustrates the Raman spectrum of this thin film, which is generated using a WITec Raman Spectroscopy (Alpha 300R) with an excitation wavelength of 487.9 nm. The low D band implies low defect density, whereas the measured intensity ratio of G band to 2D band (I_G/I_{2D}) band is about 0.2. This value is lower than 0.5, meeting the monolayer graphene condition [17].

The graphene/PMMA thin film is separated from the polymer substrate by placing a few droplets of deionized (DI) water at the edge of this thin film. The water molecules subsequently flow in between the graphene/PMMA thin film and polymer substrate. This wet graphene/PMMA thin film is thereafter detached from the polymer substrate and it is transferred into a DI water bath. The floating graphene/PMMA thin film is then carefully picked up with a piece of filter paper. Next, this graphene/PMMA thin film on the filter paper is trimmed into a smaller size sufficient to cover the core region of the single mode fiber ferrule. After that, the graphene/PMMA thin film is stamped on the core region of the single mode fiber ferrule and the filter paper is removed. The fiber ferrule with attached graphene/PMMA thin film is connected to another clean fiber ferrule through a fiber adaptor, and the transmission loss of this device is measured using a broadband amplified spontaneous emission (ASE) source (Amonics model ALS-CL-17-B-SC). The transmission loss of this device is less than 0.8 dB over 1525–1565 nm wavelength range as presented in Fig. 1(c).

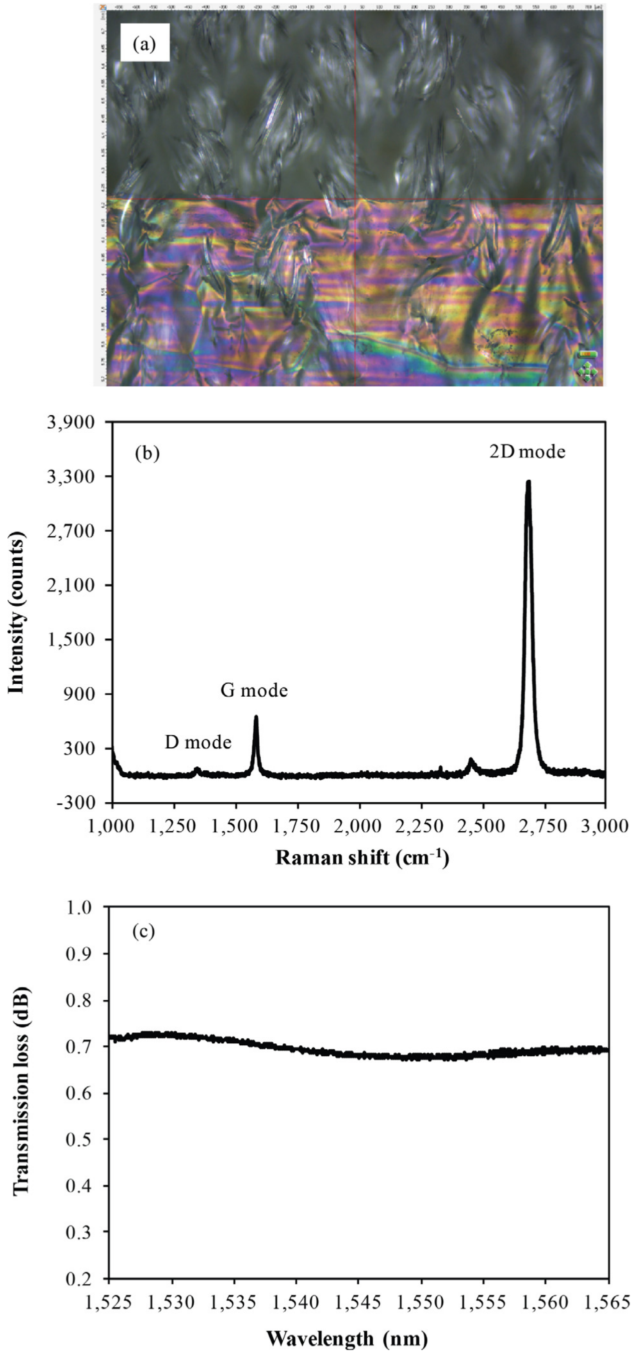

Fig. 1. (a) Image of graphene/PMMA thin film observed with 3D Profiler, (b) Raman spectrum of graphene/PMMA thin film, and (c) transmission loss of the graphene/PMMA device.

3. Multi-wavelength fiber laser setup and its performance

Fig. 2 illustrates the experimental setup of multi-wavelength EDFL. A section of 15 m EDF with an absorption coefficient of 5.5 dB/m at 1530 nm wavelength is pumped by a 980 nm laser diode via a 980/1550 nm wavelength division multiplexer (WDM). A polarization controller (PC) is employed to tune the stress-induced cavity birefringence. For intensity-dependent Kerr effect, four types of fiber-under-test (FUT) are utilized; 20 km long single-mode fiber (SMF), 5 km long dispersion compensating fiber (DCF), 50 m long PCF and 500 m long HNLF. The dispersion (D_λ), attenuation (α) and nonlinear coefficient (γ) at 1560 nm for each FUTs are summarized in Table 1.

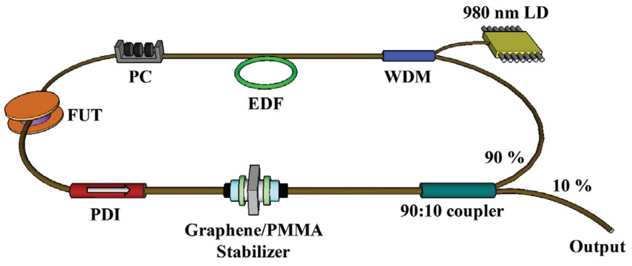

Fig. 2. Schematic diagram of multi-wavelength EDFL.