

Broadband Saturable Absorption of Graphene Oxide Thin Film and Its Application in Pulsed Fiber Lasers

Xiaohui Li, Yulong Tang, Zhiyu Yan, Yue Wang, Bo Meng, Guozhen Liang, Handong Sun, Xia Yu, Ying Zhang, Xueping Cheng, and Qi Jie Wang

Abstract—Graphene oxide (GO) has been used for optical intensity manipulation and short pulse shaping. Most interestingly, it can be used as a broadband light absorber. Such property has been systematically investigated in this paper, in a broad wavelength range from 1 to 2- μm . We fabricated one type of GO/polyvinyl alcohol (GO/PVA) film and use it as a saturable absorber (SA) in Er-, Yb-, and Tm-doped fiber ring lasers, respectively, to build pulsed fiber lasers. It is demonstrated that broad range of mode-locking in the 1- μm and 1.5- μm regions can be obtained. In addition, Q-switching around wavelength of 1870 nm can be obtained in a Tm-doped fiber ring lasers. To the best of our knowledge, this is the broadest wavelength regime in which one type of GO SA film can be used to build all-fiber pulsed ring lasers.

Index Terms—Fiber lasers, graphene oxide, mode-locking, Q-switching, modulation depth.

I. INTRODUCTION

VARIOUS carbon based materials, due to their unique and outstanding optical, magnetic, electronic and structural properties, have been intensively studied and applied in many fields, such as ultrafast optics [1]–[7], biosensing [8], optical modulator [9], and photodetector [10]–[12]. Single walled-carbon nanotube (SWNT) and graphene have been applied in ultrafast optics [12]–[24]. SWNT has also been used in the broadband technology by combining SWNTs with diameter distribution [15]. Through tuning the extra components such

as stretching CFBG, the wavelength tenability can be also achieved [23]. Very recently, single-layer graphene has been validated the intrinsic broadband operation property [25]. Among carbon based materials, graphene oxide (GO), as an excellent nonlinear optical material, can be employed for optical intensity manipulation and short pulse shaping [26]–[28]. These two characteristics are developed as optical limiters (OLs) and saturable absorbers (SAs) [28]. OL allows a low transmission at high light densities, which can be used for light protection and in sensor focal-plane. While SA gives a low absorption at high light densities, which can be used to achieve ultrashort pulses in solid state lasers, waveguide lasers, fiber lasers and even semiconductor lasers [29]–[34]. GO can be considered as an insulating and disordered analogue of a highly conducting crystalline graphene [26]. However, the fast carrier relaxation and large saturable absorption of few-layered GO indicate that oxidation mainly exists at the edge areas and has negligible effects on ultrafast dynamics and optical nonlinearities [35].

GO, as a cheap carbon material which can be mass produced, has been widely utilized in passively mode-locked lasers as a SA. Recently, GO-based passively mode-locked fiber lasers have been demonstrated in Er-doped, Yb-doped, and Tm-doped fiber lasers, respectively [31], [36]–[39]. We have reported GO walled paper absorber that was applied in the Yb-doped passively mode-locked fiber laser operating in the all-normal-dispersion (ANDI) regimes [31]. Liu *et al.* demonstrated Er-doped fiber lasers mode-locked by using a hollow-core photonics crystal fiber filled with GO solution [36]. Recently, Jung *et al.* investigated the GO SA implemented on a side-polished fiber for femtosecond pulse generation in the 2- μm region [38]. However, all the aforementioned results are reported only in one particular operation wavelength region. It is not clear whether one type of GO SA film can perform in a wide spectral range as a SA, e.g. from the 1- μm region for Yb-doped fiber (YDF) laser, to the 1.5- μm region for Er-doped fiber (EDF) laser, and up to the 1.9- μm region for Tm-doped fiber (TDF) laser. In addition, even it can operate in different wavelength regions, what would be the performance of those pulsed fiber lasers? All these questions should be answered in order to better understand the saturable absorption properties of GO so as to apply it to the implementation of high performance pulsed fiber lasers in a broadband wavelength range.

In this paper, we systematically investigated the GO SA properties by using a Ti:sapphire femtosecond laser at different wavelengths tuned by optical parametric oscillator (OPO) technique and a home-made passively mode-locked EDF laser. The optical SA property has been studied in three different wavelength

Manuscript received November 29, 2013; revised February 17, 2014 and March 9, 2014; accepted March 10, 2014. This work was supported by A*STAR SERC under Grant 112-290-4018 and A*STAR SERC Advanced Optics in Engineering Program under Grant 122 360 0004. This work was also supported in part by the CAS/SAFEA International Partnership Program for Creative Research Teams.

X. Li, Y. Tang, Z. Yan, B. Meng, and G. Liang are with the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798 (e-mail: Lixh@ntu.edu.sg; YLTANG@ntu.edu.sg; ZYAN004@e.ntu.edu.sg; bmeng1@e.ntu.edu.sg; GLIANG1@e.ntu.edu.sg).

Y. Wang and H. Sun are with the Centre for Disruptive Photonic Technologies, School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore 637371 (e-mail: YWANG28@e.ntu.edu.sg; HDSun@ntu.edu.sg).

X. Yu and Y. Zhang are with the Singapore Institute of Manufacturing Technology, Singapore 638075 (e-mail: xyu@SIMTech.a-star.edu.sg; yzhang@simtech.a-star.edu.sg).

X. Cheng is with the JPT Electronics Pte., Ltd, Singapore (e-mail: penn@jptelectronics.com).

Q. J. Wang is with the School of Electrical and Electronic Engineering and with the School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore 639798 (e-mail: qjwang@ntu.edu.sg).

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/JSTQE.2014.2312952

regimes from 1 to 2 μm . The results indicate that the GO SA truly has an ultra-broadband SA property. We investigated one GO SA film as the wall-paper absorber in three types of fiber ring lasers based on Yb-, Er-, and Tm-doped fibers, respectively. Mode-locked YDF and EDF lasers have been successfully implemented. As the YDF and EDF lasers are operated in different dispersion regimes, dissipative soliton was obtained in the YDF ring lasers, while conventional soliton was obtained in the Er-doped fiber ring lasers. Due to a higher loss in the TDF ring laser cavity, Q-switching was obtained at $\sim 1.87 \mu\text{m}$ in the current experiments. In addition, we have systematically studied the effects of the different modulation depth of GO SA, cavity loss, and gain on the performance of pulsed fiber lasers. This study reveals that one GO SA flake can be used in a broad wavelength range as an SA for potentially achieving high-performance pulsed fiber lasers.

II. GO ABSORBER PREPARATION AND ITS OPTICAL PROPERTY

In the experiments, the GO sheets, fabricated by ultrasonic agitation after chemical oxidation of graphite, consist of few atomic layers with a thickness of 0.1–5 μm (typically from 1 to 3 layers). GO wall paper absorber is prepared by using vertical evaporation method [29], [31]. The fabrication process of the GO is free of surfactant such as sodium dodecyl sulfate. GO/polyvinyl alcohol (GO/PVA) dispersion is mixed with 0.6 g PVA powder and 0.25 mg GO aqueous solution at 90 $^{\circ}\text{C}$ for 3 h. Then, the GO/PVA dispersion is poured into a polystyrene cell to evaporate for several days. After evaporation the GO/PVA SA is formed. The average thickness of GO/PVA membrane is about 30 μm . We use a small piece of the GO SA film in the passively mode-locked fiber lasers by inserting the film between two fiber connectors. In addition, the graphene oxide can also be fabricated by liquid phase exfoliation method, which is cheap and easily scalable method [40], [41].

Fig. 1(a) shows the linear transmission spectrum of GO/PVA film and PVA thin film measured by using the UV-VIS-NIR spectrometer. The GO/PVA film experiences higher losses at the wavelength regime below 500 nm. The linear transmissions at 1060, 1550, and 1900 nm are 78.1%, 83.7%, and 85.8%, respectively.

Fig. 1(b) shows the Raman spectrum of the GO/PVA SA film excited by a 532 nm laser. The spectrum shows two prominent peaks (i.e., D band at 1336 cm^{-1} , and G band at 1612.4 cm^{-1}). D band can be interpreted as the structural imperfections induced by the attachment of hydroxyl and epoxide groups on the carbon basal plane. The G band is related to the first-order scattering from the E_{2g} mode. Only a tiny 2-D band is found, indicating that the GO films of considerable thickness were coated. There are some other peaks as well as the background as seen in the Raman spectrum. They are caused by some acrylic or some other polymers in the SA films, induced in the fabrication processes.

The nonlinear SA property of GO as a function of light intensity can be expressed as [3], [42]

$$\alpha(I) = \frac{\alpha_S}{1 + I/I_s} + \alpha_{NS} \quad (1)$$

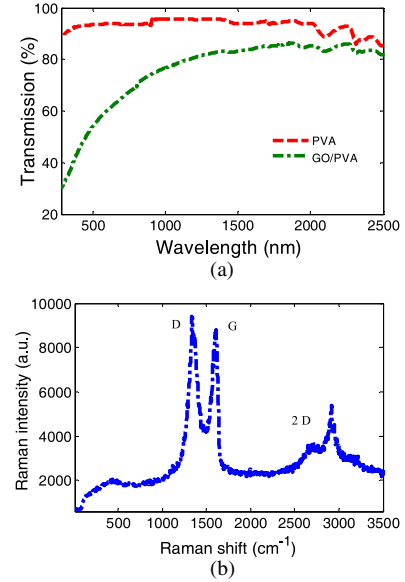


Fig. 1. (a) Linear transmission spectra of the GO/PVA films (green dashed line) and the pure PVA films (red dashed line), in the wavelength range from ~ 300 to 2500 nm. (b) Raman spectrum of GO/PVA films.

where I_s , α_S and α_{NS} are the saturation intensity, saturable, and nonsaturable absorption, respectively.

The nonlinear SA properties of GO absorber are studied by power-dependent measurements at different wavelengths with a Ti:sapphire femtosecond lasers and an OPO system. SA properties can be obviously observed with the increase of the incident light intensity. The corresponding nonlinear transmission spectrum of the GO SA is shown in Fig. 2. The nonlinear transmission of the GO absorber has been measured at three different wavelengths (i.e., 1.06, 1.5, 1.9 μm), respectively. Due to the material scattering losses and the fiber connector-induced losses, the measured minimum nonlinear transmission at low power intensity are 65.8%, 70.6%, and 72.1%, respectively. The measured values are smaller than the linear transmissions at the corresponding wavelengths as shown in Fig. 2. The modulation depths of GO SA (i.e., α_S) are 20.6% at 1.06 μm , 16.1% at 1.5 μm , and 12.8% at 1.9 μm . As seen in Fig. 2, we can calculate that the saturation intensities (i.e., I_s) of the GO SA at different wavelengths are about 1.41, 1.32, and 0.90 MW/cm^2 , respectively.

III. EXPERIMENTAL SETUP

The GO sheet was mixed with the PVA as the SA film. A piece of GO SA with size of 2 mm^2 is placed into the fiber connectors to form a mode locker. Fig. 3 shows the general experimental setup for the GO SA film applied in different rear-earth doped fiber ring lasers. The GO SA film is inserted into three different fiber ring cavities, which uses 0.8-m YDF (CorActive YB164 with core diameter of around 6 μm , cladding diameter of 125 μm , Numerical Aperture of 0.14, and Core Absorption of about 500 dB/m at 976 nm. The group velocity dispersion (GVD) is about $-43.33 \text{ ps}/\text{nm}/\text{km}$ at 1030 nm.), 0.8-EDF (Liekki Er80-8/125 with Mode Field Diameter of about

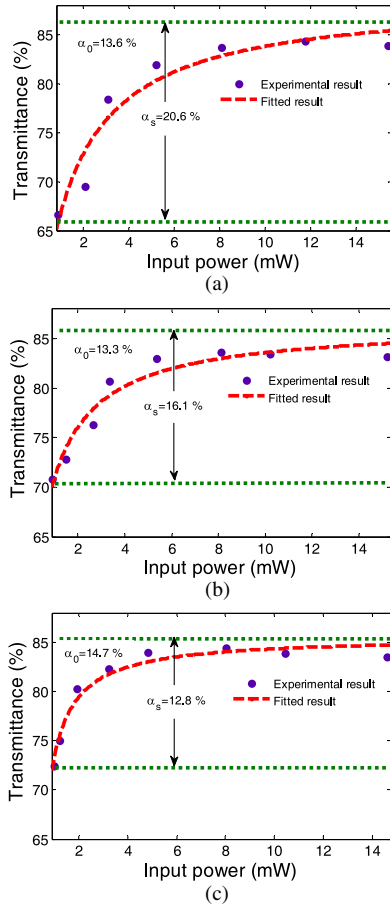


Fig. 2. Nonlinear transmissions of GO SA flake at the (a) 1060 nm, (b) 1550 nm, and (c) 1900 nm regimes, respectively.

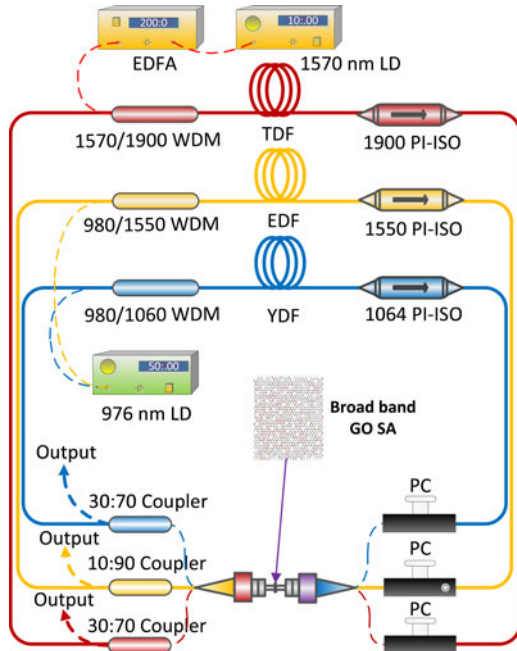


Fig. 3. Experimental setup for the three-different-wavelength (1, 1.5, and 1.9 μm) pulsed fiber laser based on GO SAs.

9.5 μm at 1550 nm, NA of 0.13, Cladding diameter of about 125 μm . The peak absorption is about 50 dB/m at 976 nm. The GVD is about $-0.02 \text{ ps}^2/\text{m}$, and 2.5-m TDF (Nefern SM-TSF-9/125 with Mode field diameter of 10.5 μm at 2000 nm, Core NA of 0.150, cut off wavelength of 1750 nm, Core Absorption of 1.5 dB/m at 1570 nm. The GVD is around 32 $\text{ps}/\text{nm}/\text{km}$ at 1800 nm.) as gain medium, respectively. The fiber lasers have total lengths of 10.7, 10.9, and 26.2 m, respectively. The rest single mode fiber (SMF) considering the pigtail of the components in each cavity are 9.9-m Corning@HI-1060 (The GVD is $-43 \text{ ps}/\text{nm}/\text{km}$ at 1030 nm), 10.1-m SMF-28 (The GVD is 17 $\text{ps}/\text{nm}/\text{km}$ at 1560), and 23.7-m SMF-28, respectively. The YDF and EDF ring lasers have used the same pump laser diode with a pump wavelength of 976-nm and a pump power of 500 mW. While the Tm-doped fiber laser is pumped by using a wavelength tunable laser at 1570 nm (Yokogawa, AQ-2200-136) and a 30-dBm EDFA as a pump laser source (Amonics, AEDFA-PM-30-B-FA). All the three fiber lasers consist of optical couplers with splitting ratios of 30:70 for the YDF laser, 10:90 for the EDF laser, and 30:70 for the TDF laser. In order to stabilize the laser output, polarization controllers (PCs) are used in each cavity. Polarization-insensitive isolators (PI-ISO) are also used in each fiber cavity. GO wall paper thin films, inserted between the fiber connectors, are used as SAs in each cavity. The EDF laser operates in the anomalous dispersion regimes with total dispersion of -0.24 ps^2 , while the YDF laser operates in the normal dispersion regime with total dispersion of 0.26 ps^2 . Because the TDF laser is operated in the $\sim 1.9 \mu\text{m}$ regime, it has a large loss in the silica fibers. The dispersion in single mode fiber (SMF-28) and TDF is also anomalous that the total dispersion of the fiber laser cavity is about -1.36 ps^2 .

The experimental results, for both YDF and EDF fiber lasers, were measured by using a commercial optical spectra analyzer (OSA Yokogawa AQ6370 A with resolution of 0.02 nm), a high speed oscilloscope (LeCroy-8600 A, bandwidth 6 GHz), a 10-GHz NIR photodetector, and a commercial autocorrelator (Alnair Labs, HAC-200). The experimental results for the TDF laser were obtained by using equipments in the corresponding wavelength regime. The OSA is Yokogawa AQ6375 (0.05-nm resolution) and the photodetector used is an InGaAs detector (DET10D).

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

When the GO SA film is inserted into the YDF ring cavities, mode-locking can be self-started at the center wavelength of 1029.5 nm in the Yb-doped fiber laser when the pump power is about 50 mW. The mode-locked fiber laser can be self-started at the pump power of 50 mW. With the increase of the pump power, single pulse mode-locking are still obtained in the experiments. Fig. 4 shows the experimental result when the pump power is about 78 mW. The spectral width is about 0.9 nm with a steep edge as shown in Fig. 4(a). The corresponding pulse trains are shown in Fig. 4(b). The pulses operated in normal-dispersion regimes have large chirps, and dissipative soliton can be formed in the fiber cavity [43]. The corresponding pulse width is about 190 ps measured with a high-speed oscilloscope as shown in

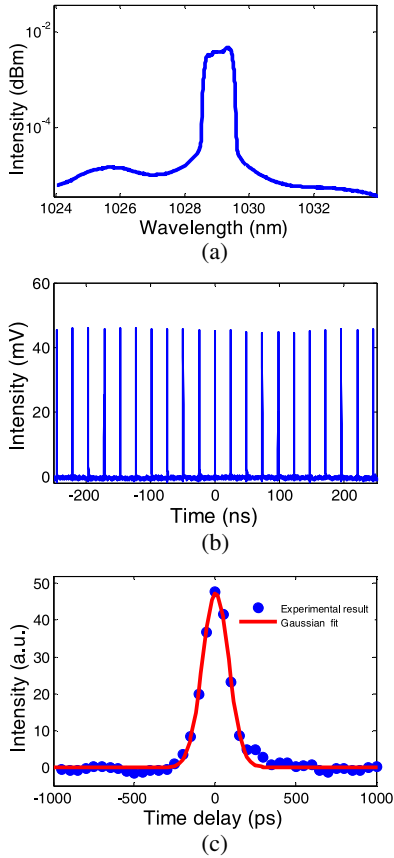


Fig. 4. Passively mode-locked Yb-doped fiber laser based on GO film at a pump power of 78 mW. (a) Spectrum, (b) the corresponding pulse train, (c) single pulse durations with measured result and Gaussian fit result. (The center wavelength is 1029.5 nm.).

Fig. 4(c). The time-bandwidth product (TBP) of the pulse is about 51, which is much larger than the transform-limited value. By changing the polarization state, the center wavelength of the mode-locking laser can be tuned accordingly which is due to the birefringence of the fiber cavities.

Then we apply the GO SA film in Er-doped passively mode-locked fiber lasers. The EDF laser operates in the wavelength of 1560 nm with pulse duration of 750.5 fs as shown in Fig. 5(a). The spectra width is about 3.8 nm, corresponding to a TBP of 0.352, which is close to the transform-limited values. The EDF laser can be self-started at pump power of 80 mW. Since the cavity operates in anomalous dispersion regime, the conventional soliton is formed in the fiber laser cavity. The suppression of the Kelly sideband is mainly due to the periodic perturbations such as gain, filtering, and loss in the fiber resonator [44].

We also applied the GO SA thin film in the Tm-doped fiber ring lasers. In the experiment, Q-switching phenomena were obtained. The results were measured by using an OSA and an In-GaAs photodetector together with an Agilent oscilloscope (The rise time is only about 25 ns). We used a laser diode at 1570 nm as a seed laser (with an optical power of about 10 mW) and an EDFA to amplify the seed laser, and then use it as a pump laser source. When the power of EDFA reaches 330 mW, Q-switching can be obtained as observed from the oscilloscope. Fig. 6(a) and

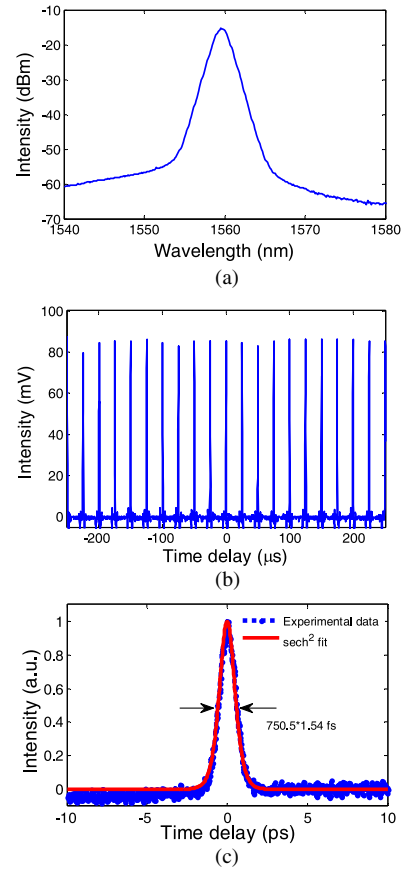


Fig. 5. Passively mode-locked Er-doped fiber laser based on the GO film at a pump power of 80 mW. (a) Spectrum (The center wavelength is 1559.6 nm), (b) corresponding pulse train, (c) autocorrelation (AC) trace of the pulse. If a sech^2 profile is assumed for fitting, the pulse duration is the width of AC trace divided by a factor of 1.54.

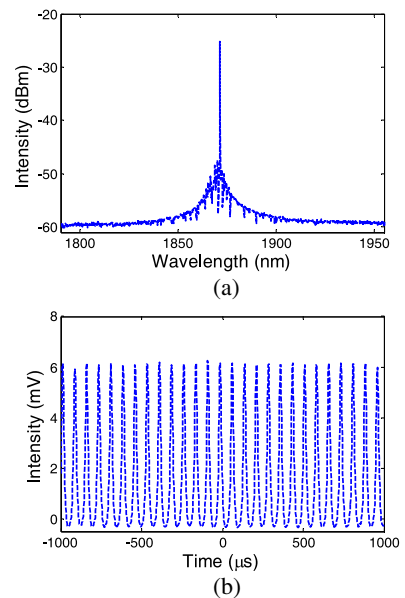


Fig. 6. Passively Q-switched Tm-doped fiber laser based on the GO SA at a pump power of 330 mW. (a) spectrum, (b) corresponding pulse train. The center wavelength is ~ 1870 nm.

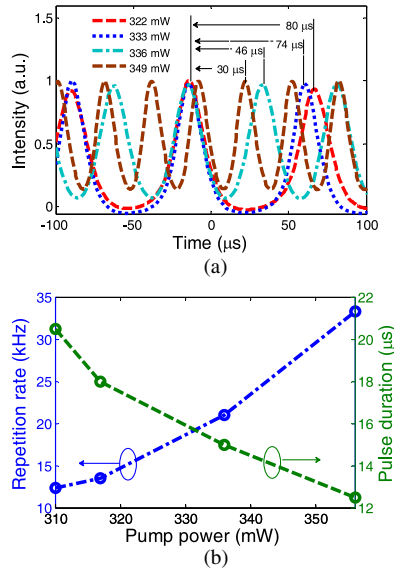


Fig. 7. (a) The oscilloscope trace with different repetition rate under different pump powers. (b) Variations of the pulse duration and repetition rate as a function of the pump powers.

TABLE I
THE SUMMARY RESULT OF THE DIFFERENT WAVELENGTH PULSE GENERATION
BASED ON ONE GO SA FILM

Gain fiber	The cavity length	Operating state	Period	Pulse duration	TBP
Yb-doped fiber	10.7 m	Mode-locking	24.4 ns	190 ps	48.4
Er-doped fiber	10.9 m	Mode-locking	24.8 ns	750.5 fs	0.352
Tm-doped fiber	26.2 m	Q-switching	30–80 μs	12.5–20.5 μs	—

(b) shows the spectra and the corresponding oscilloscope trace. The center wavelength is 1871 nm and only the substrate of the spectrum becomes broadened when Q-switching are observed in the temporal domain. The pulse width is about 35 μs, and the output power is about 20 mW.

With further increasing the power of the EDFA, the repetition rate of the Tm-doped Q-switched fiber laser increases from 12.5 to 33 kHz and the pulse width decreases from 20.5 to 12.5 μs. Fig. 7(a) shows the corresponding pulse trains observed from the oscilloscope. The variations of the pulse duration and the repetition rate are summarized in Fig. 7(b). As the pump power increases further, Q-switching operation changes to CW operation in the experiments, which may be due to the reason that it is near the damage threshold of the GO SA. We anticipate that the mode locking can be achieved by further control of the fiber cavity parameters and suitable pump power.

The experimental outputs are summarized in Table I. We can see that the cavity lengths of the Er- and Yb- doped fiber laser are almost the same. In the 1 μm regime, the pulses are generated in the dissipative soliton regime in all-normal dispersion regimes, which is due to the combined effects of the gain/loss, all normal dispersion, spectral filtering, and nonlinearity (self-phase modulation) [45]–[47]. While in the 1.5 μm regime, the mode locked

fiber laser operates in the conventional soliton regime without dispersion management. This is caused by the interaction of the anomalous dispersion, and the nonlinearity (self-phase modulation). The Q-switching in the TDF ring lasers is due to the relatively high transmission loss in this wavelength regime and the relatively low pump power. Because of the low damaged threshold of the PVA, high pump power cannot be responsible for achieving mode locking with current cavity parameters.

The pulse dynamics for these fiber lasers are different, when the GO SA is applied in different fiber cavities without intentionally managing the dispersion, the nonlinearity, and the pump strength. In order to obtain a transform-limited pulse, the Yb-doped fiber laser can also be designed to work in the conventional soliton regimes by using a piece of anomalous-dispersion component, such as grating pairs, chirped fiber Bragg gratings (CFBG) [48], hollow core photonic crystal fibers (HC-PCF) [49], or high-order-mode fibers (HOMF) [50]. On the other hand, high energy pulses can also be obtained in the 1.5 μm and the 2 μm regimes by inserting normal-dispersion components [51]–[53]. In all the operation wavelength regions, the GO/PVA film acts as a stable SA. In addition, the GO SA can also be potentially applied in the mid-infrared regime (above 3 μm), and even be potentially suitable for the THz and microwave band by controlling the oxidation degree of GO [54], [55]. It is also possible that the ultra-broadband SA will find its application in the external cavity semiconductor lasers as well as solid-state lasers [56].

V. CONCLUSION

The ultra-broadband SA property of GO/PVA films has been studied in three different wavelength ranging from 1 to 2 μm. This type of GO SA film has been investigated in three-wavelength fiber ring lasers based on Yb-, Er-, and Tm-doped fibers, respectively. The experimental results demonstrated that the modulation depths of the SA vary at different wavelengths. Mode locking of dissipative soliton and conventional soliton can be obtained at 1.06 and 1.56 μm, respectively, whereas Q-switching can be obtained at the wavelength of 1.87 μm. To the best of our knowledge, this is the broadest wavelength regime in which one type of GO SA film can operate in all-fiber pulsed ring lasers.

REFERENCES

- [1] G. C. Xing, H. C. Guo, X. H. Zhang, T. C. Sum, and C. H. A. Huan, "The physics of ultrafast saturable absorption in graphene," *Opt. Exp.*, vol. 18, pp. 4564–4573, 2010.
- [2] Z. P. Sun, T. Hasan, F. Torrisi, D. Popa, G. Privitera, F. Q. Wang, F. Bonaccorso, D. M. Basko, and A. C. Ferrari, "Graphene mode-locked ultrafast laser," *ACS Nano*, vol. 4, pp. 803–810, 2010.
- [3] F. Q. Wang, A. G. Rozhin, V. Scardaci, Z. P. Sun, F. Hennrich, I. H. White, W. I. Milne, and A. C. Ferrari, "Wideband-tunable, nanotube mode-locked, fibre laser," *Nature Nanotechnol.*, vol. 3, pp. 738–742, 2008.
- [4] A. Martinez and Z. P. Sun, "Nanotube and graphene saturable absorbers for fibre lasers," *Nature Photon.*, vol. 7, pp. 842–845, 2013.
- [5] H. Zhang, D. Y. Tang, L. M. Zhao, Q. L. Bao, and K. P. Loh, "Large energy mode locking of an erbium-doped fiber laser with atomic layer graphene," *Opt. Exp.*, vol. 17, pp. 17630–17635, 2009.
- [6] H. Zhang, Q. Bao, D. Tang, L. Zhao, and K. Loh, "Large energy soliton erbium-doped fiber laser with a graphene-polymer composite mode locker," *Appl. Phys. Lett.*, vol. 95, pp. 141103-1–141103-3, 2009.

- [7] H. Zhang, D. Y. Tang, L. M. Zhao, Q. L. Bao, K. P. Loh, B. Lin, and S. C. Tjin, "Compact graphene mode-locked wavelength-tunable erbium-doped fiber lasers: From all anomalous dispersion to all normal dispersion," *Laser Phys. Lett.*, vol. 7, pp. 591–596, 2010.
- [8] E. Morales-Narváez and A. Merkoçi, "Graphene oxide as an optical biosensing platform," *Adv. Mater.*, vol. 24, pp. 3298–3308, 2012.
- [9] M. Liu, X. B. Yin, U. A. Erick, B. S. Geng, T. Zentgraf, L. Ju, F. Wang, and X. Zhang, "A graphene-based broadband optical modulator," *Nature*, vol. 474, pp. 64–67, 2011.
- [10] F. N. Xia, T. Mueller, Y. M. Lin, A. Valdes-Garcia, and P. Avouris, "Ultrafast graphene photodetector," *Nature Nanotechnol.*, vol. 4, pp. 839–843, 2009.
- [11] Y. Z. Zhang, T. Liu, B. Meng, X. H. Li, G. Z. Liang, X. N. Hu, and Q. J. Wang, "Broadband high photoresponse from pure monolayer graphene photodetector," *Nature Commun.*, vol. 4, pp. 1811–1–11811–11, 2013.
- [12] F. Bonaccorso, Z. Sun, T. Hasan, and A. C. Ferrari, "Graphene photonics and optoelectronics," *Nature Photon.*, vol. 4, pp. 611–622, 2010.
- [13] Y. S. Fedotov, S. M. Kobtsev, R. N. Arif, A. G. Rozhin, C. Mou, and S. K. Turitsyn, "Spectrum-, pulsewidth-, and wavelength-switchable all-fiber mode-locked Yb laser with fiber based birefringent filter," *Opt. Exp.*, vol. 20, pp. 17797–17805, 2012.
- [14] S. M. Kobtsev, S. V. Kukarin, and Y. S. Fedotov, "Mode-locked Yb-fiber laser with saturable absorber based on carbon nanotubes," *Laser Phys.*, vol. 21, pp. 283–286, 2011.
- [15] S. Kivistö, T. Hakulinen, A. Kaskela, B. Aitchison, D. P. Brown, A. G. Nasibulin, E. I. Kauppinen, A. Härkönen, and O. G. Okhotnikov, "Carbon nanotube films for ultrafast broadband technology," *Opt. Exp.*, vol. 17, pp. 2358–2363, 2009.
- [16] J. Sotor, G. Sobon, I. Pasternak, A. Krajewska, W. Strupinski, and K. M. Abramski, "Simultaneous mode-locking at 1565 nm and 1944 nm in fiber laser based on common graphene saturable absorber," *Opt. Exp.*, vol. 21, pp. 18994–19002, 2013.
- [17] D. Popa, Z. P. Sun, F. Torrisi, T. Hasan, F. Wang, and A. C. Ferrari, "Sub 200 fs pulse generation from a graphene mode-locked fiber laser," *Appl. Phys. Lett.*, vol. 97, pp. 203106–1–203106–3, 2010.
- [18] A. Martinez and S. Yamashita, "10 GHz fundamental mode fiber laser using a graphene saturable absorber," *Appl. Phys. Lett.*, vol. 101, pp. 041118–1–041118–3, 2012.
- [19] T. Hasan, Z. P. Sun, F. Q. Wang, F. Bonaccorso, P. H. Tan, A. G. Rozhin, and A. C. Ferrari, "Nanotube–polymer composites for ultrafast photonics," *Adv. Mater.*, vol. 21, pp. 3874–3899, 2009.
- [20] M. Zhang, E. J. R. Kelleher, F. Torrisi, Z. Sun, T. Hasan, D. Popa, F. Wang, A. C. Ferrari, S. V. Popov, and J. R. Taylor, "Tm-doped fiber laser mode-locked by graphene-polymer composite," *Opt. Exp.*, vol. 20, pp. 25077–25084, 2012.
- [21] Z. P. Sun, D. Popa, T. Hasan, F. Torrisi, F. Wang, E. R. Kelleher, J. Travers, V. Nicolosi, and A. Ferrari, "A stable, wideband tunable, near transform-limited, graphene-mode-locked, ultrafast laser," *Nano Res.*, vol. 3, pp. 653–660, 2010.
- [22] D. Popa, Z. P. Sun, T. Hasan, F. Torrisi, F. Wang, and A. C. Ferrari, "Graphene Q-switched, tunable fiber laser," *Appl. Phys. Lett.*, vol. 98, pp. 073106–1–073106–3, 2011.
- [23] X. Liu, D. Han, Z. Sun, C. Zeng, H. Lu, D. Mao, Y. Cui, and F. Wang, "Versatile multi-wavelength ultrafast fiber laser mode-locked by carbon nanotubes," *Sci. Rep.*, vol. 3, pp. 2718–1–2718–5, 2013.
- [24] Z. P. Sun, T. Hasan, and A. C. Ferrari, "Ultrafast lasers mode-locked by nanotubes and graphene," *Physica E Low Dimens. Syst. Nanostruct.*, vol. 44, pp. 1082–1091, 2012.
- [25] B. Fu, Y. Hua, X. Xiao, H. Zhu, Z. P. Sun, and C. Yang, "Broadband graphene saturable absorber for pulsed fiber lasers at 1, 1.5 and 2 μm ," *IEEE J. Select. Topics Quantum Electron.*, vol. 20, no. 5, 2014.
- [26] K. P. Loh, Q. L. Bao, G. Eda, and M. Chhowalla, "Graphene oxide as a chemically tunable platform for optical applications," *Nature Chem.*, vol. 2, pp. 1015–1024, 2010.
- [27] N. Liaros, P. Aloukos, A. Kolokithas-Ntoukas, A. Bakandritsos, T. Szabo, R. Zboril, and S. Couris, "Nonlinear optical properties and broadband optical power limiting action of graphene oxide colloids," *J. Phys. Chem. C*, vol. 117, pp. 6842–6850, 2013.
- [28] X. F. Jiang, L. Polavarapu, S. T. Neo, T. Venkatesan, and Q. H. Xu, "Graphene oxides as tunable broadband nonlinear optical materials for femtosecond laser pulses," *J. Phys. Chem. Lett.*, vol. 3, pp. 785–790, 2012.
- [29] Y. G. Wang, H. R. Chen, X. M. Wen, W. F. Hsieh, and J. Tang, "A highly efficient graphene oxide absorber for Q-switched Nd:GdVO₄ lasers," *Nanotechnology*, vol. 22, pp. 455203–1–455203–4, 2011.
- [30] X. H. Li, Y. G. Wang, Y. S. Wang, X. H. Hu, W. Zhao, X. L. Liu, J. Yu, C. X. Gao, W. Zhang, Z. Yang, C. Li, and D. Y. Shen, "Wavelength-switchable and wavelength-tunable all-normal-dispersion mode-locked Yb-doped fiber laser based on single-walled carbon nanotube wall paper absorber," *IEEE Photonics J.*, vol. 4, no. 1, pp. 234–241, Feb. 2012.
- [31] X. H. Li, Y. G. Wang, Y. S. Wang, Y. Z. Zhang, K. Wu, P. P. Shum, X. Yu, Y. Zhang, and Q. J. Wang, "All-normal-dispersion passively mode-locked Yb-doped fiber ring laser based on a graphene oxide saturable absorber," *Laser Phys. Lett.*, vol. 10, pp. 075108–1–075108–5, 2013.
- [32] C. A. Zaug, Z. P. Sun, D. Popa, S. Milana, T. Kulmala, R. S. Sundaram, V. J. Wittwer, M. Mangold, O. D. Sieber, M. Golling, Y. Lee, J.-H. Ahn, A. C. Ferrari, and U. Keller, "Wavelength tunable graphene modelocked VECSEL," presented at the CLEO, San Jose, CA, USA, 2013, Paper CW1G.4.
- [33] R. Mary, G. Brown, S. J. Beecher, F. Torrisi, S. Milana, D. Popa, T. Hasan, Z. P. Sun, E. Lidorikis, S. Ohara, A. C. Ferrari, and A. K. Kar, "1.5 GHz picosecond pulse generation from a monolithic waveguide laser with a graphene-film saturable output coupler," *Opt. Exp.*, vol. 21, pp. 7943–7950, 2013.
- [34] S. J. Beecher, R. R. Thomson, N. D. Psaila, Z. P. Sun, T. Hasan, A. G. Rozhin, A. C. Ferrari, and A. K. Kar, "320 fs pulse generation from an ultrafast laser inscribed waveguide laser mode-locked by a nanotube saturable absorber," *Appl. Phys. Lett.*, vol. 97, pp. 111114–1–111114–3, 2010.
- [35] X. Zhao, Z. B. Liu, W. B. Yan, Y. P. Wu, X. L. Zhang, Y. S. Chen, and J. G. Tian, "Ultrafast carrier dynamics and saturable absorption of solution-processable few-layered graphene oxide," *Appl. Phys. Lett.*, vol. 98, pp. 121905–1–121905–3, 2011.
- [36] Z. B. Liu, X. Y. He, and D. N. Wang, "Passively mode-locked fiber laser based on a hollow-core photonic crystal fiber filled with few layered graphene oxide solution," *Opt. Lett.*, vol. 36, pp. 3024–3026, 2011.
- [37] J. Xu, J. Liu, S. Wu, Q.-H. Yang, and P. Wang, "Graphene oxide mode-locked femtosecond erbium-doped fiber lasers," *Opt. Exp.*, vol. 20, pp. 15474–15480, 2012.
- [38] M. Jung, J. Koo, J. Park, Y.-W. Song, Y. M. Jhon, K. Lee, S. Lee, and J. H. Lee, "Mode-locked pulse generation from an all-fiberized, Tm-Ho-codoped fiber laser incorporating a graphene oxide-deposited side-polished fiber," *Opt. Exp.*, vol. 21, pp. 20062–20072, 2013.
- [39] X. Y. He, Z. B. Liu, D. N. Wang, M. W. Yang, C. R. Liao, and X. Zhao, "Passively mode-locked fiber laser based on reduced graphene oxide on microfiber for ultra-wide-band doublet pulse generation," *J. Lightw. Technol.*, vol. 30, no. 7, pp. 984–989, Apr. 2012.
- [40] F. Bonaccorso, A. Lombardo, T. Hasan, Z. P. Sun, L. Colombo, and A. C. Ferrari, "Production and processing of graphene and 2 d crystals," *Mater. Today*, vol. 15, pp. 564–589, 2012.
- [41] F. Bonaccorso and Z. P. Sun, "Solution processing of graphene, topological insulators and other 2 D crystals for ultrafast photonics," *Opt. Mater. Exp.*, vol. 4, pp. 63–78, 2014.
- [42] E. Garmire, "Resonant optical nonlinearities in semiconductors," *IEEE J. Sel. Topics Quantum Electron.*, vol. 6, no. 6, pp. 1094–1110, Nov./Dec. 2000.
- [43] X. H. Li, Y. S. Wang, W. Zhao, X. L. Liu, Y. G. Wang, Y. H. Tsang, W. Zhang, X. H. Hu, Z. Yang, C. X. Gao, C. Li, and D. Y. Shen, "All-fiber dissipative solitons evolution in a compact passively Yb-doped mode-locked fiber laser," *J. Lightw. Technol.*, vol. 30, no. 15, pp. 2502–2507, Aug. 2012.
- [44] L. E. Nelson, D. J. Jones, K. Tamura, H. A. Haus, and E. P. Ippen, "Ultrashort-pulse fiber ring lasers," *Appl. Phys. B*, vol. 65, pp. 277–294, 1997.
- [45] P. Grelu and N. Akhmediev, "Dissipative solitons for mode-locked lasers," *Nature Photon.*, vol. 6, pp. 84–92, 2012.
- [46] E. J. R. Kelleher, J. C. Travers, Z. P. Sun, A. G. Rozhin, A. C. Ferrari, S. V. Popov, and J. R. Taylor, "Nanosecond-pulse fiber lasers mode-locked with nanotubes," *Appl. Phys. Lett.*, vol. 95, pp. 111108–1–111108–3, 2009.
- [47] E. J. R. Kelleher, J. C. Travers, E. P. Ippen, Z. P. Sun, A. C. Ferrari, S. V. Popov, and J. R. Taylor, "Generation and direct measurement of giant chirp in a passively mode-locked laser," *Opt. Lett.*, vol. 34, pp. 3526–3528, 2009.
- [48] X. H. Li, Y. S. Wang, W. Zhang, W. Zhao, X. H. Hu, Z. Yang, C. X. Gao, X. L. Wang, X. L. Liu, D. Y. Shen, and C. Li, "Low-repetition-rate ytterbium-doped fiber laser based on a CFBG from large anomalous to large normal dispersion," *Laser Phys.*, vol. 21, pp. 2112–2117, 2011.

- [49] X. Liu, J. Lagsgaard, and D. Turchinovich, "Monolithic highly stable Yb-doped femtosecond fiber lasers for applications in practical biophotonics," *IEEE J. Sel. Topics Quantum Electron.*, vol. 18, no. 4, pp. 1439–1450, Jul./Aug. 2012.
- [50] J. W. Nicholson, S. Ramachandran, and S. Ghalimi, "A passively-modelocked, Yb-doped, figure-eight, fiber laser utilizing anomalous-dispersion higher-order-mode fiber," *Opt. Exp.*, vol. 15, pp. 6623–6628, 2007.
- [51] X. Liu, "Mechanism of high-energy pulse generation without wave breaking in mode-locked fiber lasers," *Phys. Rev. A*, vol. 82, pp. 053808-1–053808-5, 2010.
- [52] P. Wan, L. M. Yang, and J. Liu, "High pulse energy 2 μm femtosecond fiber laser," *Opt. Exp.*, vol. 21, pp. 1798–1803, 2013.
- [53] S. Kobtsev, S. Kukarin, and Y. Fedotov, "Ultra-low repetition rate mode-locked fiber laser with high-energy pulses," *Opt. Exp.*, vol. 16, pp. 21936–21941, 2008.
- [54] Z. Zheng, C. Zhao, S. Lu, Y. Chen, Y. Li, H. Zhang, and S. Wen, "Microwave and optical saturable absorption in graphene," *Opt. Exp.*, vol. 20, pp. 23201–23214, 2012.
- [55] S. Chen, C. Zhao, Y. Li, H. Huang, S. Lu, H. Zhang, and S. Wen, "Broadband optical and microwave nonlinear response in topological insulator," *Opt. Mater. Exp.*, vol. 4, pp. 587–596, 2014.
- [56] C. A. Zaug, Z. P. Sun, V. J. Wittwer, D. Popa, S. Milana, T. S. Kulmala, R. S. Sundaram, M. Mangold, O. D. Sieber, M. Golling, Y. Lee, J. H. Ahn, A. C. Ferrari, and U. Keller, "Ultrafast and widely tuneable vertical-external-cavity surface-emitting laser, mode-locked by a graphene-integrated distributed Bragg reflector," *Opt. Exp.*, vol. 21, pp. 31548–31559, 2013.

Xiaohui Li received the B.S. degree in science from Northwest University, Xi'an, China, in 2006. He received the Ph.D. degree from the Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences and Xi'an Jiaotong University, Xi'an, Shaanxi, China, in 2012. He is currently a Research Fellow at Nanyang Technological University. His current research interests include passively mode-locked fiber laser, high power fiber laser, and solitons in fiber.

Yulong Tang received the Ph.D. degree in optical engineering from the Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, China, in 2008. From 2008 to 2011, he was a Research Assistant at the Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, where he was engaged in the development of mid-IR solid-state lasers. Since 2011, he has been working at Shanghai Jiao Tong University as an Assistant Professor, engaged in research upon high-power fiber lasers and solid-state lasers, and application of laser technologies. His current research interests include mid-IR laser sources and nonlinear optical dynamics.

Zhiyu Yan was born in Yunnan, China, in 1987. She received the B.Sc. degree in electronics information and technology from Beijing Normal University, Beijing, China, in 2010 and the M.Sc. degree in electronics from Nanyang Technological University, Singapore, in 2012. She is currently working toward the Ph.D. degree at Nanyang Technological University, Singapore. Her research interests include fiber laser, supercontinuum generation.

Yue Wang received the B.S. degree from Sichuan University, Chengdu, China. He is currently working toward the Ph.D. degree in photonics at Nanyang Technological University, Singapore. His research interests include the study of linear and nonlinear optical properties of semiconductor quantum dots, nanowires, and 2-D nanomaterials.

Bo Meng was born in Liaoning, China, in 1984. He received the B.S. degree in optical information science and technology from Harbin Engineering University, Harbin, China, and the M.S. degree from the Harbin Institute of Technology, Harbin, China, in 2007 and 2009, respectively. He is currently working toward the Ph.D. degree in microelectronics at the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. His current research interests include the development of tunable singlemode quantum cascade laser devices, physics and modulation of semiconductor lasers, mid-infrared plasmonics, and microfabrication.

Guozhen Liang was born in Fujian, China, in 1986. He received the B.S. degree in physics from the University of Science and Technology of China, Hefei, China, in 2010. He is currently working toward the Ph.D. degree in microelectronics at the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. His current research interests include the development of high performance terahertz quantum cascade lasers, terahertz plasmonics, and integrated graphene devices.

Handong Sun is currently an Associate Professor at the School of Physical and Mathematical Science since 2007. He received the Bachelor's degree in physics from the Dalian University of Technology, Master's and the Ph.D. degrees from the Huazhong University of Science and Technology, and Hong Kong University of Science and Technology, respectively. His research interests include optoelectronic materials and devices, semiconductor physics; optical spectroscopy; nano-materials and technology.

Xia Yu received the B.Eng. and Ph.D. degrees from the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore, in February 2003 and April 2007, respectively. From June 2006 until September 2008, she worked as a Postdoctoral Researcher in the school of EEE, NTU. She is currently an Assistant Research Scientist in the Precision Measurements Group, Singapore Institute of Manufacturing Technology (SIMTech), Agency for Science Technology and Research (A*STAR). Her research interests include photonic crystal-based devices, microstructured waveguides, photonic sensors, and surface plasmons.

Ying Zhang received the B.Eng., M.Eng., and Ph.D. degrees from Southeast University, China, in 1989, 1992, and 1995, respectively. From 1996 to 1997, he was a postdoctoral fellow with Nanyang Technological University. Since 1998, he has been working with Singapore Institute of Manufacturing Technology, now as a Senior Scientist, the Group Manager of Precision Measurements Group, the Division Director of Manufacturing Automation Division, and the Director of Research Liaison Office of SIMTech. He received the National Outstanding Doctoral Dissertation Award from the State Council of China in 1999; the Best Project Award of Photonics Europe'2004 from European Commission and SPIE in 2004; the IES Prestigious Engineering Achievement Award in 2005, and the Best Paper Awards in a number of international conferences. He has published more than 100 referred journal papers in his research areas. His current research interests include optical measurements, near-field optics, adaptive control and signal processing, image processing, X-ray optics, and ultra-fast lasers.

Xueping Cheng received the B.Eng. and M.Eng. degrees from the Optoelectronics Engineering Department, Huazhong University of Science and Technology, China, in 1997 and 2001, respectively. He received the Ph.D. degree from Network Technology Research Centre, Nanyang Technological University, Singapore. After receiving the M.Eng. degree, he carried out research in the FBG-based devices design and package in Network Technology Research Centre, Nanyang Technological University, Singapore. In early 2003, he joined Hewlett-Packard Singapore Pvt., Ltd., and worked in the area of Laser Ablation and MEMS package. His research is mainly focused on the high power fiber laser.

Qi Jie Wang received the Ph.D. degree in electrical and electronic engineering from Nanyang Technological University, Singapore, in 2005. After the Ph.D. degree, he worked at NTU. From 2007 to 2009, he joined the School of Engineering and Applied Science, Harvard University, in Prof. Federico Capasso's Group as a Postdoctoral Researcher. In October 2009, he was a joint Nanyang Assistant Professor at the School of Electrical and Electronic Engineering (Microelectronics Division) and the School of Physical and Mathematical Sciences (Physics and Applied Physics Division). His current research interests are to explore theoretically and experimentally nano-structured semiconductor and fiber-based materials, and nanophotonic devices (nanoplasmonics, photonic crystals, and metamaterials) with an emphasis on investigating the fundamental properties (optical and electrical) of semiconductor and high power fiber lasers, and nanophotonic devices in the infrared frequency regimes.