Hafnium Bismuth Erbium Co-Doped Fiber Based Dark Pulses Generation With Black Phosphorus As Saturable Absorber

A Ahmad*, M F A Rahman1, M A M Johari1, A A Latiff2, M H Jalil2, H H M Yusof3, X S Cheng4, A R Muhammad5, and S W Harun6

1Fakulti Teknologi Kejuruteraan Elektrikal dan Elektronik, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
2Fakulti Kejuruteraan Elektronik dan Kejuruteraan Komputer, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
3Fakulti Kejuruteraan Elektrik, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
4School of Engineering, KDU University College, Utropolis, Glenmarie Jalan Kontraktor U1/14, Shah Alam, Selangor Darul Ehsan, Malaysia.
5Institute of Microengineering and Nanoelectronics (IMEN), University Kebangsaan Malaysia, 43600 UKM, Bangi Selangor, Malaysia
6Department of Electrical Engineering, University of Malaya, 50603, Kuala Lumpur, Malaysia

*Corresponding author’s email: aminah@utem.edu.my

Abstract A dark pulse generation is demonstrated in a fiber laser configured with a 20 cm long HBEDF and multilayer Black Phosphorus as a gain medium and saturable absorber, respectively. Dark pulses fiber laser at 1.5 µm region was obtained when the pump power exceeds the threshold of 147 mW. Meanwhile, the spectrum of the dark pulse is centred at 1556.40 nm, with the 3 dB bandwidth of 0.12 nm and the separation between adjacent pulses is 1145 ns, corresponding to the cavity length of 211 m. The pulse width was measured to be around 320 ns. The radio-frequency spectrum of the dark pulse, which was measured within the 20 MHz range, more than 17 harmonics were observed within this range, which indicates the mode-locking operation of the laser. The fundamental frequency was obtained at 1.1 MHz, which agreed with the oscilloscope trace. Furthermore, it shows a signal to noise ratio of about 36.58 dB, which indicates good stability. The maximum output power of 0.78 mW and pulse energy of 0.78 nJ were obtained at 187 mW pump power.

Keywords: Fiber lasers, Dark pulsed laser, Mode-locking.

1. Introduction
The advantages of compactness and flexibility of fiber lasers have drawn widespread attention. Most of the applications used is being practised in many applications such as in optical communication, fiber sensor technologies, micromachining and the military system [1-3]. Q-switching and mode locking are mostly used by these applications. Compared to the conventional active technique, passive mode-locked is desirable through the usage of a saturable absorber (SA) which produce an ultrashort pulsed fibre laser[4]. This is due to the rapid modulation of the resonator compared to any electronic modulator which is necessary for an actively mode-locked laser [4]. Recently, numerous types of saturated absorbing materials are used for pulse laser generation, including semiconductor saturable absorber mirror (SESAM) [5], single-walled carbon nanotubes (SWCNTs) [6] and graphene [7, 8].
Most of the researchers have used semiconductor saturable absorber mirrors (SESAMs) for passively generating mode locked lasers even though their fabrication process is complicated and expensive [9]. In addition, the operating wavelength depends on the semiconductor materials. Nowadays popular passive techniques are SWCNTs and graphene. However, the SWCNTs SA operation wavelength is determined by the nanotube diameter and the bandgap engineering was complicated, which normally lead to an uncontrollable non-saturable loss. Meanwhile, graphene has higher electron mobility and zeroes energy bandgap, which allows broadband operation. However, its optical absorption is located weakly at 1.5 µm region, so its application in the optical communication area may be limited. Apart from SWCNTs and graphene, many other nanomaterials have been investigated in fiber laser systems as SA devices, such as topological insulators, transition metal dichalcogenides and black phosphorus (BP). BP have a narrow direct band-gap and wide optical response from infrared to mid-infrared that corresponds to the bulk of layers and single, respectively [4].

There is also interest in the generation of dark pulse lasers that are less sensitive to fiber loss compared to bright pulse [9, 10]. Dark Pulse laser emits a steady beam of light, with periodic dips in the continuous bright background. This type of lasers are new, so their applications are still under investigation [11]. Optical frequency combs and optical atomic clocks are some of the applications for dark pulse lasers. The frequency of dark pulse waves could be used to transfer information. Meanwhile, the continuous-wave background may provide a single strong comb line that could be used to probe a quantum transition. In telecommunications, some applications can be used due to the lack of dispersion and linearity during the transmission of dark pulses [12].

Many works have been previously reported on the generation of dark pulses. For instance, Wang et al. demonstrated the generation of dark pulses in a mode-locked Erbium-doped fiber laser (EDFL) based on a Molybdenum disulfide film based saturable absorber (SA) where the laser was at a 1.7 MHz repetition rate [13]. In another work, Zhao et al. produced dark pulses by using rhenium disulfide (ReS₂) as a saturable absorber [14].

Mode-locked fiber lasers operating at 1.5 µm region were demonstrated using 20 cm long Hafnium Bismuth Erbium Doped Fiber (HBEDF) as a gain medium in conjunction with the newly developed passive saturable absorber. The HBEDF was achieved by the combination of Hf, Bi, and Er doped yttria alumina-silica glass based preform, which have absorption loss at 980 nm is found to be 100 dB/m equivalent to 12,500 wt ppm [15, 16] Here, the pulse generation was realised using Black Phosphorus as a saturable absorber.

2. Methodology
2.1 Pulse generation with BP SA
In 2D nanomaterials, BP has gained much interest in recent years as a potential in many applications. The multilayer BP has good optical characteristics such as wideband absorption and ultrafast carrier dynamics. Furthermore, it comprises only the elemental "phosphorus", and thus it could be easily peeled off by mechanical exfoliation. The BP SA was prepared by transferring multilayer BP onto a fiber ferrule tip using a mechanical exfoliation method. At first, thin flakes were moderately peeled off from a big block of commercially available BP crystal (purity of 99.995 %) using clear scotch tape. Then, the flakes were repeatedly pressed so that they adhered onto the scotch tape to form a thin layer of BP. Afterwards, an end surface of fresh standard FC/PC fiber ferrule tip was pressed down on the scotch tape to transfer the multilayer BP onto it. The BP transferring process is described in Figure 1 (a). Next, the ferrule with multilayer BP was connected to another fresh FC/PC fiber ferrule via a fiber adapter to form an all-fiber BP based SA device. A tiny amount of index matching gel was applied at the connector to minimise the SA device loss. The energy dispersive spectroscopy (EDS) analysis was used to examine the composition of the multilayer BP tape [17]. The presence of BP material on the scotch tape adhesive surface was confirmed by the presence of the high peak of phosphorus in the spectroscopy, as shown in Figure 1 (b). Figure 1 (c) shows the FESEM image of the multilayer BP tape, which confirmed the existence of uniform multilayer phosphorus on the tape.
2.2 Laser Cavity Configuration

The laser cavity has a typical ring configuration, as shown in Figure 2. It uses a passive BP SA for mode-locking. A 20 cm HBEDF piece was pumped with a 980 nm laser diode via 980nm/1550nm wavelength division multiplexer (WDM). It produced an amplified spontaneous emission (ASE) photons, which oscillated in the laser cavity to produce lasing at 1550 nm region. The SA functions as a mode-locker to convert the continuous-wave lasing to nanosecond pulses. A polarisation insensitive optical isolator was incorporated inside the ring cavity to lock the propagation of light in one direction and thus to prevent any detrimental effects due to spurious reflections inside the resonator. A 198 m long single mode fiber (SMF) coupler was also inserted to increase the nonlinearity so that enough phase shift per round trip can be achieved in the cavity for assisting the mode-locking operation. A 10 dB output coupler was used to split the output power in the portion of 90% and 10%. The 90% portion was channelled back into the cavity for further oscillation, while 10% portion was tapped out as the output.

The spectral and temporal analysis of the Q-switched EDFL was carried out using a 0.02 nm resolution OSA (Yokogawa AQ6370C) and a high-speed photodetector linked to an oscilloscope (GWINSTEK: GDS-3352), respectively. A 7.8 GHz Radio Frequency (RF) spectrum analyser (Anritsu MS2683A) was used to measure the repetition rate and evaluate the stability of the pulse laser. The average laser power was measured by an optical power meter (Thorlabs PM 100D) coupled with an InGaAs powerhead operating between 800-1700 nm (Photodiode Power Sensor S145C Integrating Sphere).
Figure 2. Experimental setup of the mode-locked fiber laser for dark pulses generation

3. Results and Discussion

In this experiment, the dark pulses were obtained when the pump power exceeds the threshold of 147 mW. As shown in Figure 3, the spectrum of the dark pulse is centred at 1556.40 nm, with the 3 dB bandwidth of 0.12 nm. Compared to CW operation (without the SA), the operating wavelength was slightly shifted to a shorter wavelength due to the insertion loss of the SA. Figure 4 displays the mode-locked pulse train, which indicates obvious dark pulses. The separation between adjacent pulses is 1145 ns, corresponding to the cavity length of 211 m. The pulse width was measured to be around 320 ns. The formation of dark pulses is most probably due to the deployment of highly nonlinear HBEDF in a long cavity. The cavity design provides an independent polarisation nature. Thus, the two orthogonal polarisation components inevitably exist and couple to each other, inducing the generation of the dark pulses. Figure 5 illustrates the radio-frequency spectrum of the dark pulse, which was measured within the 20 MHz range. More than 17 harmonics were observed within this range, which indicates the mode-locking operation of the laser. The fundamental frequency was obtained at 1.1 MHz, which agreed with the oscilloscope trace. It shows a signal to noise ratio of about 36.58 dB, which indicates good stability.
Figure 3. Output spectra of the fiber laser with and without SA at a pump power of 147 mW.

Figure 4. Typical oscilloscope trace for the dark pulses.
Figure 5. RF spectrum of the dark pulses

Figure 6. shows the output laser power and pulse energy versus the pump power. When the pump power is below the 147 mW, only continuous wave (CW) operation happens. Continuously increasing the pump power from 147 to 187 mW, a stable mode-locking operation is observed. Both output power and pulse energy increase with the rise of pump power. The maximum output power of 0.78 mW and pulse energy of 0.78 nJ were obtained at 187 mW pump power. The mode-locking operation ceases with a further increase in pump power above 187 mW.

Figure 6. Output power and pulse energy of the mode-locked laser against pump power

4. Conclusion
This research demonstrates a dark pulse generation in a fiber laser configured with a 20 cm long HBEDF and Black Phosphorus as a gain medium and saturable absorber, respectively. The dark pulses fiber laser at 1.5 µm region was obtained when the pump power exceeds the threshold of 147 mW. The spectrum of the dark pulse is centred at 1556.40 nm, with the 3 dB bandwidth of 0.12 nm. The separation between adjacent pulses is 1145 ns, corresponding to the cavity length of 211 m. The pulse width was measured to be around 320 ns. The radio-frequency spectrum of the dark pulse, which was measured within the 20 MHz range. The maximum output power of 0.78 mW and pulse energy of 0.78 nJ were obtained at 187 mW pump power. Dark pulse lasers are new, so applications for them are
still a matter of speculation. Some of the possible applications, for instance, are related to optical frequency combs and optical atomic clocks.

5. References

[1] M. A. M. Johari, M. H. B. Jali, H. H. B. M. Yusof, H. R. B. A. Rahim, A. B. Ahmad, M. I. M. A. Khudus, et al., "Polyvinyl alcohol coating microbottle resonator on whispering gallery modes for ethanol liquid sensor," *Optics & Laser Technology*, vol. 143, p. 107379, 2021.

[2] M. H. Jali, H. R. A. Rahim, M. A. M. Johari, A. Ahmad, H. H. M. Yusof, S. H. Johari, et al., "Integrating microsphere resonator and ZnO nanorods coated glass for humidity sensing application," *Optics & Laser Technology*, vol. 143, p. 107356, 2021.

[3] M. B. Hisyam, M. F. M. Rusdi, A. A. Latiff, and S. W. Harun, "Generation of mode-locked ytterbium doped fiber ring laser using few-layer black phosphorus as a saturable absorber," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 23, pp. 39-43, 2016.

[4] A. Markom, S. Tan, A. Muhammad, M. C. Paul, A. Dhar, S. Das, et al., "Dark pulse mode-locked fibre laser with zirconia-based erbium-doped fibre (Zr-EDF) and Black phosphorus saturable absorber," *Optik*, vol. 223, p. 165635, 2020.

[5] U. Keller, K. J. Weingarten, F. X. Kartner, D. Kopf, B. Braun, I. D. Jung, et al., "Semiconductor saturable absorber mirrors (SESAM's) for femtosecond to nanosecond pulse generation in solid-state lasers," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 2, pp. 435-453, 1996.

[6] S. W. Harun, M. A. Ismail, F. Ahmad, M. F. Ismail, R. M. Nor, N. R. Zulkepely, et al., "A Q-Switched Erbium-Doped Fiber Laser with a Carbon Nanotube Based Saturable Absorber," *Chinese Physics Letters*, vol. 29, p. 114202, 2012.

[7] H.-P. Li, H.-D. Xia, Z.-G. Wang, X.-X. Zhang, Y.-F. Chen, S.-J. Zhang, et al., "A compact graphene Q-switched erbium-doped fiber laser using optical circulator and tunable fiber Bragg grating," *Chinese Physics B*, vol. 23, p. 024209, 2014.

[8] J. Zhao, Y. Wang, P. Yan, S. Ruan, Y. Tsang, G. Zhang, et al., "An Ytterbium-doped fiber laser with dark and Q-switched pulse generation using graphene-oxide as saturable absorber," *Optics Communications*, vol. 312, pp. 227-232, 2014/02/01/ 2014.

[9] B. Nizamani, S. Salam, A. Jafry, N. Zahir, N. Jurami, M. A. Khudus, et al., "Indium tin oxide coated D-shape fiber as a saturable absorber for generating a dark pulse mode-locked laser," *Chinese Physics Letters*, vol. 37, p. 054202, 2020.

[10] Z. C. Tiu, S. J. Tan, H. Ahmad, and S. W. J. O. C. L. Harun, "Dark pulse emission in nonlinear polarization rotation-based multiwavelength mode-locked erbium-doped fiber laser," vol. 12, p. 113202, 2014.

[11] Y. S. Kivshar and B. J. P. r. Luther-Davies, "Dark optical solitons: physics and applications," vol. 298, pp. 81-197, 1998.

[12] J. Yu, L. Xu, Y.-K. Yeo, P. N. Ji, T. Wang, and G.-K. Chang, "A novel scheme for generating optical dark return-to-zero pulses and its application in a label switching optical network," *IEEE photonics technology letters*, vol. 18, pp. 1524-1526, 2006.

[13] R. Wang, Y. Yao, Q. Wu, Y. Yang, J. Tian, and K. Xu, "Bright-dark pulses produced by passively mode-locked fiber laser with Molybdenum disulfide saturable absorber," in *Advanced Laser Technology and Applications*, 2018, p. 108440J.

[14] R. Zhao, G. Li, B. Zhang, and J. J. O. e. He, "Multi-wavelength bright-dark pulse pair fiber laser based on rhenium disulfide," vol. 26, pp. 5819-5826, 2018.

[15] A. Ahmad, X. S. Cheng, M. C. Paul, A. Dhar, S. Das, H. Ahmad, et al., "Investigation of the Brillouin effect in highly nonlinear hafnium bismuth erbium doped fiber," *Microwave and Optical Technology Letters*, vol. 61, pp. 173-177, 2019.
[16] A. Ahmad, S. W. Harun, M. C. Paul, M. Rusdi, S. Das, A. Dhar, et al., "Bismuth-doped fiber as Q-switcher in hafnium bismuth erbium co-doped fiber laser," Microwave and Optical Technology Letters, vol. 62, pp. 3634-3639, 2020.

[17] T. A. Alghamdi, S. Adwan, H. Arof, and S. W. Harun, "Application of black phosphorus for pulse generation in erbium-doped fiber laser," Results in Optics, vol. 4, p. 100091, 2021.

Acknowledgements
The authors are grateful to Universiti Teknikal Malaysia Melaka for the research and financial support. The work is funded by Research Development Grant Scheme RAGS/1/2014/SG04/UTEM/2.