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PAPER

Optical modulation in Er-doped fiber laser delivering dark pulse utilizing side polished fiber coated with Ti_3AlC_2 as saturable absorber

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Abstract

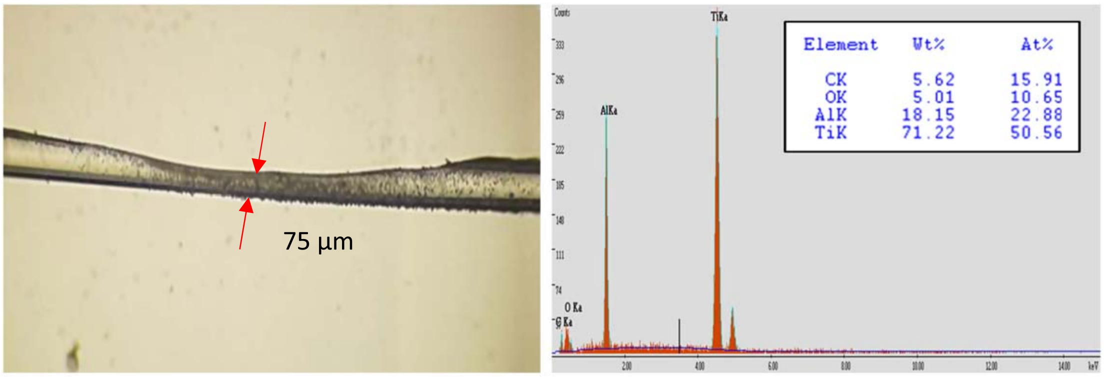
Dark pulse mode-locked Erbium doped fiber laser (EDFL) was demonstrated in this work by employing side polished fiber (SPF) coated with Ti_3AlC_2 solution using drop casting method. The modulation depth of fabricated SPF coated with Ti_3AlC_2 solution was characterized at 2.2%. This SPF coated structure allowed the formation of dark mode-locked pulse with improved the birefringence and nonlinearity in EDFL. The dark pulse generated was cubic-quintic nonlinear Schrödinger equation (CQNLSE) dark pulse with center wavelength at 1558.935 nm, repetition rate 1.839 MHz and pulse width 170.2 ns. Pulse stability was examined, revealing a high signal to noise ratio (SNR) of 65.86 dB. This work could serve as a foundation for the development of sustainable industry, innovation and infrastructure.

Introduction

Optical pulse is the key element across variety of applications covering optical communication, sensing, metrology, material processing and medical surgery [1–4]. With the burst of connected devices to applications such as Internet of Things (IoT), ultrafast femto-second pulse is indeed necessary to offer high speed data with low latency for future 5 G/6 G optical communication technologies [5, 6]. Nevertheless, bright optical pulse tends to suffer from Self Phase Modulation (SPM) when propagating in long haul distance which will cause signal broadening, and eventually puts a limit on data bit rate.

Contrary to bright pulse, dark pulse exhibits dip at strong background. This unique feature allows dark pulse to propagate stably when noise is present and is not sensitive to fiber loss [7]. Dark pulse in single mode fiber (SMF) was firstly observed in an experiment conducted by Emplit in 1987 [8]. Following the success, dark pulse was proven to have superior performance in Brillouin time domain analysis (BOTDA), gyroscope and coherent Wavelength Division Multiplexing (WDM). Dark pulse displayed improved resolution, accuracy and acquisition time over conventional BOTDA system, with 20 mm resolution and accuracy $\pm 20\ \mu\varepsilon$ was recorded experimentally [9]. Coherent WDM communication using 64 quadrature amplitude modulation was demonstrated using dark pulse Kerr comb from micro-resonator by Attira *et al* [10]. High conversion efficiency from the Kerr comb structure allowed optical signal-to-noise ratio above 33 dB, while maintaining on chip pump power of few hundred milliwatts.

Many works were reported on various bright pulse from fiber laser but the formation of dark pulse is more demanding in a sense that it requires precise setting's of cavity parameters with the aid of saturable absorber (SA) or artificial SA. Generally, dark pulse can be categorized into three types, namely nonlinear Schrodinger equation (NLSE), Cubic-Quintic nonlinear Schrodinger equation (CQNLSE) and domain wall dark pulse [11, 12]. These dark pulse formations are distinct from each other, in terms of the requirements in a laser cavity. CQNLSE dark pulse is much



(a) (b)

Figure 1. (a) microscope image of SPF with waist diameter of 75 μm (b) EDS analysis of Ti_3AlC_2 coated SPF.

easier to be generated with the assistance of novel materials regardless of the cavity's dispersion. Various emerging materials namely graphene [13, 14], Transition Metal Dichalcogenides (TMD) [15, 16], Topological Insulator (TI) [17, 18], Black Phosphorus (BP) [19], MAX phase [20, 21] and MXene [22, 23] were reported to offer saturable absorption and high nonlinearity properties. So far, these materials are inserted into fiber laser cavity by the means of thin film [24] or coated on side polished fiber (SPF) [25–27].

Recently, MAX phase materials are extensively investigated in photonics and electronics. Their naturally special metallic-covalent-ionic bonding cause them to display the properties of both metal and ceramic. Therefore, they have high temperature resistance like ceramic and have excellent electrical and thermal conductivity like metal. Compared to other materials [28–30] MAX phase exhibited low density, high modulus elasticity, good oxidation resistance and high melting point. These properties of MAX phase promote them as promising material to be used in high temperature applications. Various types of MAX phase such as V_2AlC [21], Ti_3AlC_2 [31], Ti_2AlN [32] and Ta_4C_3 [33] were proven as effective SA for mode-locking laser. Here, we report the generation of CQNLSE dark pulse from a fiber laser system using MAX phase Ti_3AlC_2 solution coated on a SPF. Ti_3AlC_2 used in this work is capable to generate dark pulse owing to its high order nonlinearity induced when light interacted with it within SPF [34]. Additionally, Ti_3AlC_2, belonging to MAX phase material has been proven to induce short pulse in fiber laser system [32, 35, 36]. The interaction of evanescence field and Ti_3AlC_2 provides ample nonlinearity to meet the requirement of CQNLSE dark pulse formation. The frequency and pulse width of the generated dark pulse are 1.839 MHz and 170.2 ns, respectively. To the best of our knowledge, this is the first demonstration of dark pulse fiber laser using MAX phase Ti_3AlC_2. This study reveals the potential of Ti_3AlC_2 SA for dark pulse generation in fiber laser system.

Fabrication of side polished fiber and characterization of Ti_3AlC_2 SA

A custom polisher designed in-house was used to fabricate SPF. Components of the custom polisher were mounted on aluminium base plates to ensure stability during polishing process. The speed of the rotary dremel tool was controlled by a variable DC power supply. A piece of 50 cm SMF was firmly mounted on two elevated optical fiber platforms to ensure the fiber was level and under tension while its surface was being polished by 600-gret sandpaper. After the silica fiber had been mounted on the optical fiber platform, two ends of the fiber were connected to an amplified spontaneous emission (ASE) light source emitting in the range of 1550 nm at one end and an optical power meter (OPM) at the other end. Once the optical power was observed to be stable, the speed of the rotary dremel tool was slowly increased until the polymer buffer can be seen to have deposited on the sandpaper. During the grinding process, the power was monitored periodically until the ideal 3 dB loss was achieved. The grinding process usually required 45 min to complete but it varied depending on the speed of the rotary tool. Figure 1(a) illustrates the fabricated SPF taken with microscope at 4X magnification. The diameter of the SPF was approximately 75 μm.

As for material preparation, Ti_3AlC_2 was purchased from Forsman Scientific Co. Ltd, with 99% purity. 25 mg of Ti_3AlC_2 powder was weighed using a weighing scale then placed into a glass container containing 10 ml of deionized water (DI). A magnetic stirrer was also placed in the container. The mixture was stirred for 2 h at 500 rpm under room temperature. The solution was then extracted from the glass container with a pippet and 3 μl were applied to the fiber's polished area using drop-casting method. The area was then allowed to air-dry for 24 h. The energy-dispersive x-ray spectroscopy (EDS) was carried out on the Ti_3AlC_2 coated SPF to confirm the

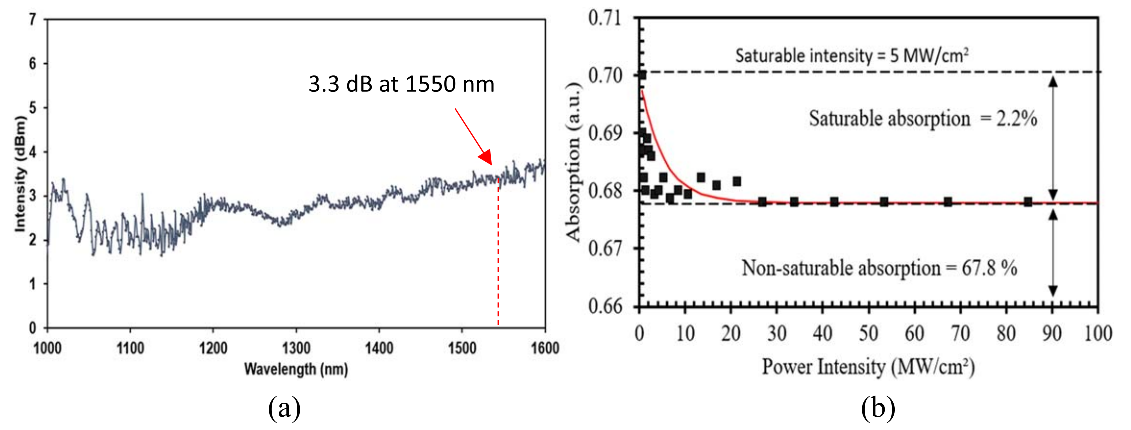


Figure 2. (a) Linear absorption spectrum (b) nonlinear characterization of Ti_3AlC_2 coated SPF.

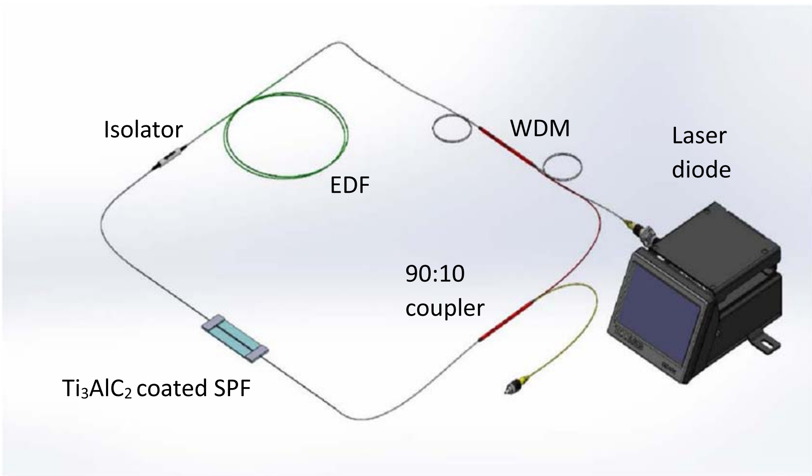


Figure 3. Experimental setup of the mode-locked EDFL with Ti_3AlC_2 coated SPF.

elements of the material. The EDS result is represented by figure 1(b), with Ti and Al recorded 71.22 wt and 18.15 wt, respectively. Figures 2(a) and (b) illustrate the linear and nonlinear absorption of the Ti_3AlC_2 coated SPF SA. The SA had a linear absorption of 3.3 dB at 1550 nm. The SA has a modulation depth of 2.2%, a saturation intensity of 5 MW cm^{-2} and non-saturable loss of 67.8%. Two-arms approach with pulse source of 1559 nm, 1.8 ps pulse duration and 1.8 MHz repetition rate was used to characterize the nonlinear characteristics.

Experimental setup

Figure 3 illustrates the experimental setup of dark pulse generation in mode-locked EDFL. A 1 m of Erbium doped fiber (EDF) with dispersion −21.64 ps/(nm.km) was used as gain medium to emit lasing in C-band region. The EDF was pumped with a 980 nm laser diode via 980/1550 nm Wavelength Division Multiplexer (WDM). An isolator was used to force lasing in one direction. A 50 m long SMF was inserted into the ring cavity to provide Kerr nonlinearity and non-Kerr nonlinearity. The fabricated Ti_3AlC_2 coated SPF was connected between the 50 m SMF and 90:10 coupler to act as a SA and a nonlinear medium. The 90% output of the coupler was looped to the 1550 nm input of the WDM whilst the 10% output was used for collecting the data on various measuring instruments such as optical spectrum analyzer (OSA, Yokogawa AQ6360B), oscilloscope (LeCroy 352A) and 7.8 GHz radio frequency analyzer (RFSA, Anritsu MS2683A). The cavity length was estimated to be around 81 m long. Except for the 1 m long EDF, the remaining cavity was constructed with SMF. The cavity operated in the anomalous dispersion region.

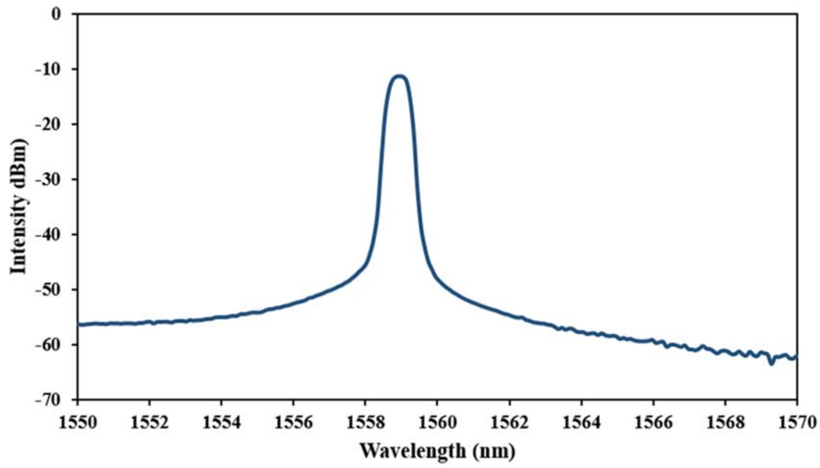


Figure 4. Optical spectrum of the mode-locked EDFL with Ti_3AlC_2 coated SPF.

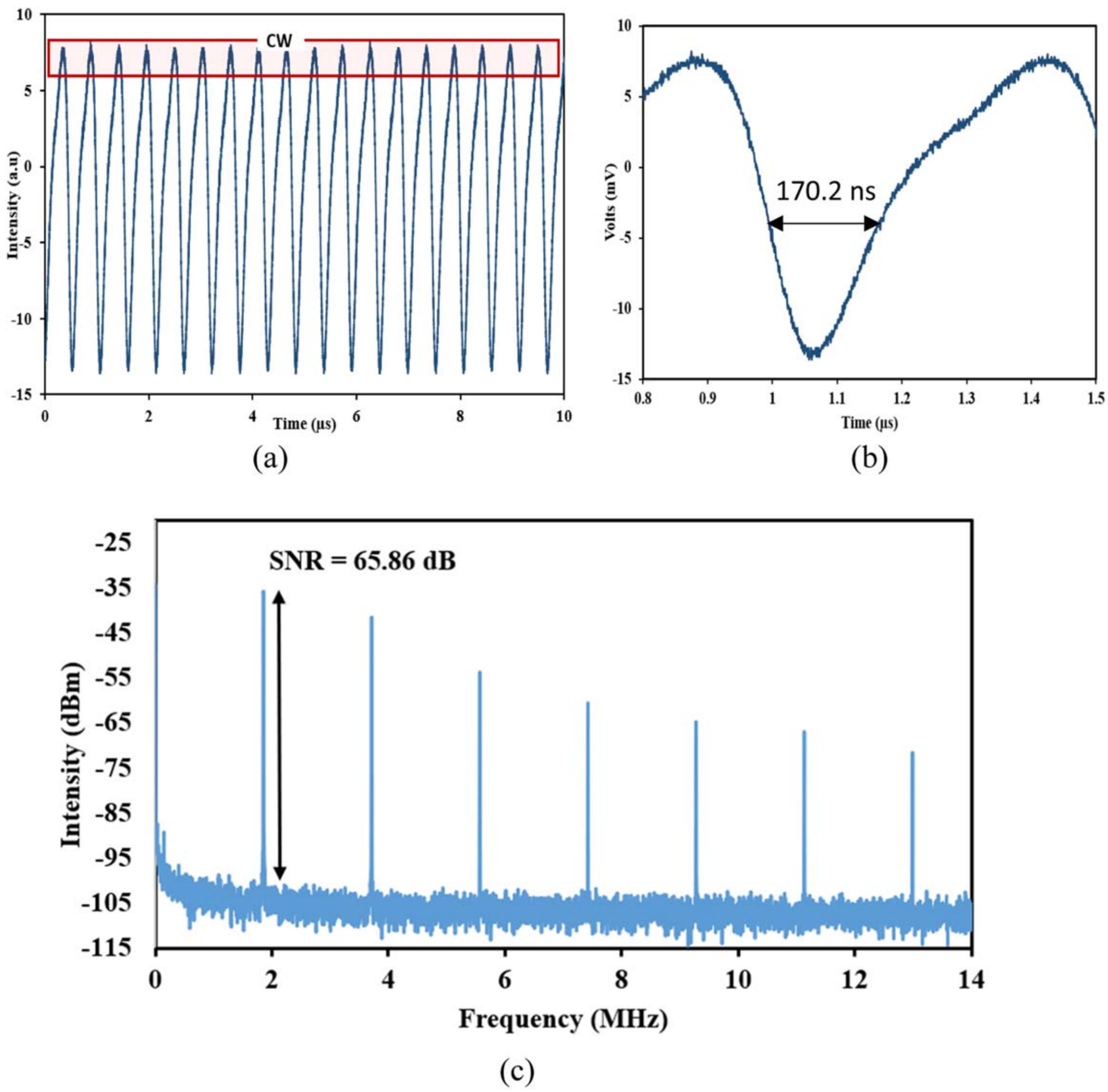


Figure 5. (a) Pulse train of dark pulse (b) zoom in of single dark pulse (c) RF spectrum of mode-locked EDFL with Ti_3AlC_2 coated SPF at 270 mW.

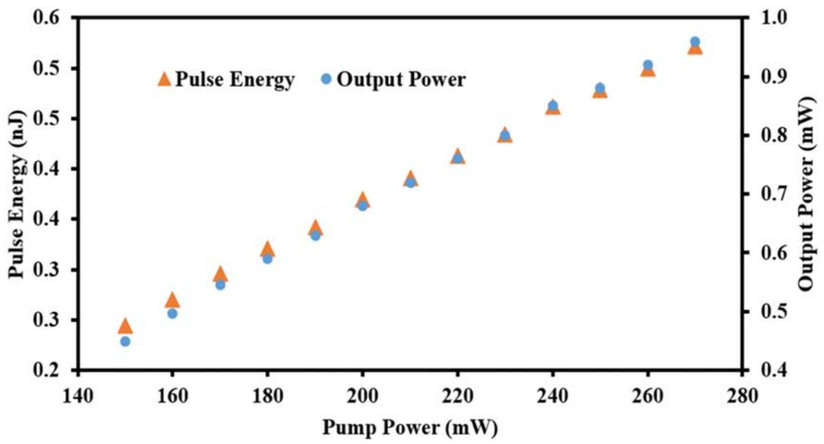


Figure 6. Output power and the pulse energy versus pump power of mode-locked EDFL with Ti_3AlC_2 coated SPF.

Results and discussion

Pump power was gradually increased, and when it reached 145 mW, the continuous wave (CW) spectrum broadened due to self phase modulation (SPM) in the fiber laser cavity. This indicated the commencement of mode-locking operation. The laser was able to self-start when the SPF coated Ti_3AlC_2 SA was inserted into the cavity. At low pump power, SPF coated Ti_3AlC_2 SA was transparent for laser cavity modes. Nevertheless, as the intensity was increased, the SA would start to absorb high intensity modes while the weaker modes grew and oscillated. This process eventually locked all multiple longitudinal modes together, and produced burst of pulses. As the pump power was further increased to the maximum available pump power at 270 mW, pulsing was still present. Only CW signal was observed when Ti_3AlC_2 coated SPF was removed from the laser cavity. This affirmed that pulsing was initiated by Ti_3AlC_2 SPF. Figure 4 illustrates the mode-locked spectrum at 270 mW, with center wavelength 1558.935 nm. Figure 5(a) shows the pulse train of the mode-locked laser at oscilloscope. From the figure, the repetition rate was revealed at 1.839 MHz. The repetition rate was maintained throughout pump power 145 mW to 270 mW. This repetition rate was tallied with the cavity length, indicating that the pulse was oscillating at its fundamental frequency.

In figure 5(b), the pulses are below the noise floor, confirming that the pulse generated is dark pulse. The measured dark pulse width was ascertained at 170.2 ns. Dark pulse was generated due to the nonlinearity provided by Ti_3AlC_2 coated SPF. It enhances the interaction of pulse light with the highly nonlinear Ti_3AlC_2 via evanescent field. The stability of dark pulse was further confirmed with Radio Frequency Spectrum Analyzer (RFSA). Figure 5(c) reveals SNR of 65.86 dB at its repetition rate. This affirmed the stability of the dark pulse. Both output power and pulse energy were found to be increasing with pump power, which can be seen in figure 6. Highest recorded output power was 0.96 mW. The pulse energy was found to increase from 0.285 nJ to 0.53 nJ for pump power ranging from 145 mW to 270 mW.

Conclusion

In this work, dark pulse was generated from an EDFL with the incorporation with Ti_3AlC_2 coated SPF which served as SA. The fabricated SPF enhanced the birefringence and nonlinearity of the EDFL through the interaction of pulse light with Ti_3AlC_2 solution coated on the SPF. This interaction facilitated the generation of CQNLSE dark pulse. The dark pulse laser operated at wavelength of 1558.935 nm, with a repetition rate of 1.839 MHz and pulse duration of 170.2 ns. The obtained pulse width can be made narrower by optimizing the material fabrication process. To the best of our knowledge, this is the first demonstration of CQNLSE dark pulse employing Ti_3AlC_2 SA. The ability of Ti_3AlC_2 coated SPF as SA for dark pulse generation showed promising potential for optical communication and time domain spectroscopy applications.

Acknowledgments

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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