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# Adaptable Optical Fiber Displacement-Curvature Sensor Based on a Modal Michelson Interferometer with a Tapered Single Mode Fiber

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**Abstract:** A compact, highly sensitive optical fiber displacement and curvature radius sensor is presented. The device consists of an adiabatic bi-conical fused fiber taper spliced to a single-mode fiber (SMF) segment with a flat face end. The bi-conical taper structure acts as a modal coupling device between core and cladding modes for the SMF segment. When the bi-conical taper is bent by an axial displacement, the symmetrical bi-conical shape of the tapered structure is stressed, causing a change in the refractive index profile which becomes asymmetric. As a result, the taper adiabaticity is lost, and interference between modes appears. As the bending increases, a small change in the fringe visibility and a wavelength shift on the periodical reflection spectrum of the in-fiber interferometer is produced. The displacement sensitivity and the spectral periodicity of the device can be adjusted by the proper selection of the SMF length. Sensitivities from around 1.93 to 3.4 nm/mm were obtained for SMF length between 7.5 and 12.5 cm. Both sensor interrogations, wavelength shift and visibility contrast, can be used to measure displacement and curvature radius magnitudes.

**Keywords:** fiber optic sensor; modal optical fiber Michelson interferometer; displacement-curvature measurement

## 1. Introduction

Optical fiber sensors applied to the measurement of physical, chemical, and biological parameters have been a subject of great interest since they have special advantages such as simplicity, compactness, immunity to electromagnetic field, easy construction, fast response, resistance to hazard environments, and real time measurement, among others. Moreover, mechanical bending is an important physical parameter to be measured in order to determine deformations, displacements, and curvature radius for high resolution optical instrumentation processes. In recent years, several bending sensors

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# Lossy Mode Resonance Generation on Sputtered Aluminum-Doped Zinc Oxide Thin Films Deposited on Multimode Optical Fiber Structures for Sensing Applications in the 1.55 µm Wavelength Range

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**Abstract:** In this work, we demonstrated lossy mode resonance (LMR) generation in optical fiber structures based on multimode fibers coated with aluminum-doped zinc oxide (AZO) films. AZO thin films were deposited by using radio frequency magnetron sputtering. In order to exhibit the usefulness of the LMR effect for sensing applications in optical fiber based systems, the deposition conditions of the AZO film coatings were set to obtain the second LMR order within the 1.55 µm wavelength range. An optical transmission configuration setup was used to investigate the LMR effect on fiber structures based on the use of no-core and cladding-removed multimode fibers coated with AZO films synthesized from metallic sputtering targets with different proportions of Zn:Al, 92:8% and 98:2%, at atomic concentrations. The optical and electrical/chemical features of the AZO films were characterized with UV–vis and XPS spectroscopy, respectively. The optical response of the proposed sensing configuration to refractive index (RI) variations was experimentally demonstrated. For the best approach, the sensitivity of wavelength displacement to RI variations on the liquid surrounding media was found to be 1214.7 nm/RIU.

**Keywords:** lossy mode resonance; aluminum-doped zinc oxide; optical fiber sensors; multimode fiber; reactive RF magnetron sputtering

## 1. Introduction

The progress in optical fiber technology has transformed the field of sensing and measurements because of advantages such as compact design, increased user safety due to electrically passive operation, immunity to electromagnetic interference, fast response, high sensitivity, wide sensing range, and remote sensing capabilities, among others. Optical fiber based configurations have demonstrated their reliability for physical, chemical, and biological sensing [1,2]. Currently, the process of thin-film deposition onto optical fibers has been of increasing interest for applications in the realm of optical sensing. Several deposition techniques, combined with the advent of new special fibers and novel materials, have attracted a renewed interest in that area. In this case, optical sensing is achieved by detecting electromagnetic resonances generated by the coupling between a mode guided within the fiber and a mode of the material coating. Depending on the permittivity of the thin-film material, phenomena

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Letter

# Magnetron sputtered Al-doped ZnO thin film as saturable absorber for passively Q-switched Er/Yb double clad fiber laser

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**Abstract**

The passive Q-switched operation of a ring cavity Er/Yb-doped double clad fiber laser by using an Al-doped ZnO (AZO) thin film as saturable absorber is experimentally demonstrated. In order to improve the absorbance in the C-band wavelength region, a thin film of AZO containing Zn and Al metal precursors in a proportion of 98:2 wt% was developed by an radio-frequency (RF) magnetron sputtering process. Then the AZO film was used as a saturable absorber (SA) in a ring cavity Er/Yb double clad fiber laser. The AZO-SA exhibits a modulation depth of 11.3% and a saturation intensity of 0.057 MW $cm^{-2}$ in the 1.55 $\mu$m waveband. In a pump power range from 0.475 to 1.356 W, stable Q-switched pulse trains with repetition rates of 70.1–161.3 kHz were observed. With a maximum pump power of 1.356 W, a minimum pulse width of 1.12 $\mu$s and a maximum pulse energy of 1.32 $\mu$J are obtained. To the best of our knowledge, we present the first demonstration of a passive Q-switching laser operation using an RF sputtered AZO thin film as a saturable absorber. The reliability of the RF magnetron sputtered AZO thin films used as an SA for 1.55 $\mu$m Q-switched laser applications is experimentally demonstrated.

Keywords: fiber lasers, Q-switching, Al-doped zinc oxide, radio-frequency (RF) magnetron sputtering, saturable absorber

(Some figures may appear in colour only in the online journal)

## 1. Introduction

Investigations of Q-switched fiber lasers have been of persistent interest to generate short high-energy laser pulses with applications in different research areas, such as remote sensing, medicine, optical communications, and material processing, among others [1–3]. Q-switched laser emission can be achieved by passive and active techniques. Passive Q-switched (PQS) laser pulses are obtained by using a saturable absorber (SA) element, which passively varies the quality factor in the laser cavity. Then, PQS lasers are simple, compact and cost-effective systems compared with active Q-switched lasers, which require the use of additional electronic equipment. Different SA devices, including semiconductor saturable absorber mirrors [4, 5], graphene [6, 7], carbon nanotubes [8, 9], rare-earth-doped fibers [10, 11], transition

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# Single and dual-wavelength noise-like pulses with different shapes in a double-clad Er/Yb fiber laser

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**Abstract:** We report an experimental study of passive harmonic mode-locking in an all-fiber switchable dual-wavelength Er/Yb double-clad laser. The proposed scheme supports single- and dual-wavelength operation of mode-locked pulses with rectangular, h-like and trapezoidal shapes in a noise-like pulse regime. Single-wavelength emissions at $\lambda_1$ = 1545.1 and $\lambda_2$ = 1563.6 nm were obtained for pump power values of 9.42 and 6.31 W, achieving pulse durations of up to 18 and 11.8 ns, respectively. At an intermediary pump power of 7.5 W, dual-wavelength emission is obtained and pulses of around 3.59 ns are generated. Additionally, the transition dynamics until 4th-order harmonic mode-locking is also observed. Different laser operation regimes of fundamental and different orders of harmonic mode-locking, with rectangular, h-shaped or trapezoidal shaped pulses are obtained with the same laser configuration with simple and well-defined plates and pump power adjustments.



## 1. Introduction

The operation characteristics of a passively mode-locked fiber laser (PMLFL) allows the generation of coherent and stable waveforms, including conventional and dispersion-managed solitons [1], and a variety of dissipative solitons [2]. Moreover, quasi-stable patterns of solitons involved in dynamics such as soliton rain [3] and noise-like pulses (NLPs) [4] were also demonstrated, even in symbiotic or multiple-soliton (MS) regimes depending of their packet-forming mechanism or their coherence nature [5]. Due to their stability, compactness and ease of use, nowadays PMLFLs have become fundamental devices in optics and materials laboratories around the world. However, the limited average output power originated from the low gain provided by single-mode active fibers is a challenge to overcome [6]. In this sense, rare-earth-doped double-clad fibers used as gain media has proved to be a reliable option to significantly increase the gain factor and efficiency of single-mode fiber lasers operation by using cladding pumping from high-power multimode sources [7].

In recent years, different laser regimes from harmonic generation [8,9] to the formation of different soliton patterns [10] passing by dissipative soliton resonance (DSR) [11–13], or

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PHOTONICS Research

# Fiber laser with simultaneous multi-wavelength Er/Yb passively *Q*-switched and single-wavelength Tm gain-switched operations

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**We report the experimental investigation of an all-fiber multi-wavelength passively *Q*-switched Er/Yb laser with simultaneous gain-switched pulsed operation by using a thulium-doped fiber as a saturable absorber. Laser emission is obtained in three wavelength regions with central peaks at around 1546 nm, 1561 nm, and 1862 nm. Multi-wavelength emission with separation of approximately 1 nm is obtained around the wavelength regions of 1546 nm and 1561 nm. Stable laser pulses are generated in the pump power range from 3.6 W to 7.3 W.** 

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## 1. INTRODUCTION

Fiber lasers operating in wavelength regions of 1.5-μm and 2-μm have attracted great attention because of their potential applications in many research areas and industries such as medical surgery [1–3], optical communications [4], material processing [5], sensing and lidar [6,7], and spectroscopy [8], among others [9,10]. Among the techniques used to produce a pulsed light emission, *Q*-switching is one of the most preferred [11–19]. *Q*-switched fiber lasers can be designed to generate high-energy optical pulses with durations in the nanosecond range, which can be obtained by implementing both passive and active methods. In the last decade, passively *Q*-switched (PQS) operation of fiber lasers has been achieved by using un-pumped rare-earth-doped and co-doped fibers as fiber saturable absorbers (FSAs). This passive technique allows designing simple all-fiber laser systems [20]. In this technique, the laser configurations maintain advantages of cost-effectiveness, high efficiency, and free maintenance; in addition, no intra-cavity components are needed, which makes them compact and simple. Moreover, in recent years, gain switching (GS) has become a promising effective technique to obtain short high-energy laser pulses. GS laser operation is achieved by laser gain on–off commutation when a modulated pump source is used [21]. Then, the characteristics of the pulsed laser emission can be controlled, since the pulsed pump source directly modulates population inversion in the energy levels of the gain medium [20]. In this regard, *Q*-switching lasers, used as pump sources, allow the generation of GS laser pulses to achieve pulsed high-energy light emission in the 2-μm region. Because of the different absorption bands of a Tm-doped fiber (TDF), GS laser emission near the 2-μm waveband can be achieved with a TDF laser (TDFL) with a modulated pump source at different operation wavelengths. Taking advantage of the in-band pump and absorption characteristics of the TDF, fast transition from $^3H_6$ energy level to the $^3F_4$ upper laser level can be reached. As a result, the cavity gain is switched on and off almost at the same time as the pump pulse [22], where stable GS laser pulse trains can be obtained, as reported in Refs. [23–26]. GS laser operation has been demonstrated by using a 1.55-μm modulated pump source, from which the shortest GS pulse of 10 ns was obtained in a scheme including a 20-cm-long TDF as the gain medium [23]. Approaches with simultaneous GS and mode-locking (ML) operation in Tm/Ho co-doped fiber laser configurations also have been reported [10,20]. Recently, our research group demonstrated a fiber laser setup with simultaneous $Tm^{3+}$ PQS and $Ho^{3+}$ GS operation [27].

In this paper, we experimentally demonstrate simultaneous PQS and GS operations of a fiber laser by using an Er/Yb double-clad fiber (EYDCF) and a TDF within the same linear cavity. Stable PQS pulses in the 1.55-μm wavelength region and GS pulses in the 1.8-μm region are obtained. The TDF

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# Reconfiguration of the multiwavelength operation of optical fiber ring lasers by the modifiable intra-cavity induced losses of an in-fiber tip probe modal Michelson interferometer

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**Abstract**

A straightforward and versatile method for switching from single to different multiwavelength laser emission in ring cavity fiber lasers is proposed and demonstrated experimentally. The method is based on using the changeable interference pattern from an optical fiber modal Michelson interferometer as a wavelength selective filter into the ring cavity laser. The interferometer is constructed using a bi-conical tapered fiber and a single-mode fiber segment, with these being spliced together to form an optical fiber tip probe. When the length of the single-mode fiber piece is modified, the phase difference between the interfering modes of the interferometer causes a change in the interferometer free spectral range. As a consequence, the laser intra-cavity losses lead to gain competition, which allows us to adjust the number of simultaneously generated laser lines. A multiwavelength reconfiguration of the laser from one up to a maximum of eight emission lines was obtained, with a maximum SNR of around 47 dBm.

Keywords: fiber lasers, wavelength filtering, erbium-ytterbium doped fiber, fiber design and fabrication

(Some figures may appear in colour only in the online journal)

## 1. Introduction

Multiwavelength fiber lasers sources have been widely investigated due to their special characteristics, such as low cost, versatility, wide wavelength tuning range, narrow line-width, fast response, high reliability, and simple service-free operation [1–4]. They have been of considerable interest due to their potential applications in a number of fields, including wavelength division multiplexing systems, fiber-optic communications, optical fiber sensors, optical component testing,

 

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# All-Fiber Laser Curvature Sensor Using an In-Fiber Modal Interferometer Based on a Double Clad Fiber and a Multimode Fiber Structure

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**Abstract:** An all-fiber curvature laser sensor by using a novel modal interference in-fiber structure is proposed and experimentally demonstrated. The in-fiber device, fabricated by fusion splicing of multimode fiber and double-clad fiber segments, is used as wavelength filter as well as the sensing element. By including a multimode fiber in an ordinary modal interference structure based on a double-clad fiber, the fringe visibility of the filter transmission spectrum is significantly increased. By using the modal interferometer as a curvature sensitive wavelength filter within a ring cavity erbium-doped fiber laser, the spectral quality factor Q is considerably increased. The results demonstrate the reliability of the proposed curvature laser sensor with advantages of robustness, ease of fabrication, low cost, repeatability on the fabrication process and simple operation.

**Keywords:** fiber optic laser sensor; modal in-fiber interferometer; curvature measurement; erbium-doped fiber laser

## 1. Introduction

In-fiber modal interferometers used as optical fiber spectral filters have been of persistent interest for their application in optical communication systems, optical instrumentation, and fiber lasers design. Specially, they have been attracted wide attention in fiber sensing because their many advantages such as high sensitivity, immunity to electromagnetic field, small size, low-cost, low maintenance required, and long term operation. Different approaches of fiber sensors designed with in-fiber structures used as wavelength filter as well as sensing element has been reported to measure refractive index (RI) [1–3], curvature [4–7], temperature [8], displacement/strain [9,10], and simultaneous or different physical parameters with the same configuration [11–14]. In particular, in-fiber curvature sensors have been of increasing interest for applications such as monitoring of smart and composite engineering structures, robotics, prosthetics design, medical treatment, and industrial metrology, among others.

An in-fiber structure based on modal interference used as sensing device requires a fiber element to recombine the excited coupled modes from cladding with the core modes producing

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# Tunable narrow linewidth all-fiber thulium-doped fiber laser in a 2 $\mu$m-band using two Hi-Bi fiber optical loop mirrors

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**Abstract**

We propose an all-fiber Tm-doped fiber laser with a tunable and narrow laser line generated in a wavelength region of 2 $\mu$m. A single laser line with a linewidth below 0.05 nm, tunable in a wavelength range of 44.25 nm, is obtained. The laser linewidth and the discrete wavelength tuning range depend on the characteristics of the two fiber optical loop mirrors with high birefringence in the loop that forms the cavity. Dual-wavelength laser operation is also observed at tuning range limits with a wavelength separation of 47 nm. Alternate wavelength switching is also observed.

Keywords: fiber lasers, fiber interferometers, thulium-doped fiber, wavelength tuning

(Some figures may appear in colour only in the online journal)

## 1. Introduction

Fiber lasers operating at 2 $\mu$m have been of increasing interest due to the special features offered by this spectral window, including high transparency to atmosphere, eye-safe emission, and efficient interaction with human/animal tissues [1–4]. In this regard, thulium-doped fiber lasers (TDFL) have attracted interest because they meet those operation features in a potential bandwidth from 1.8–2.1 $\mu$m with easier thermal management and a high nonlinear threshold, making them attractive in areas such as light detection and ranging and medical applications [5–8]. Since fiber components compatible with 2 $\mu$m laser generation are readily accessible, all-fiber TDFL interest has increased due to the possibility of designing more robust and compact fiber laser systems. Due to the possibility of obtaining laser emission in a bandwidth of 300 nm, the tuning of the generated laser wavelength in a wide range is the foremost advantage of TDFLs for optical instrumentation applications at the 2 $\mu$m waveband. Different approaches of all-fiber tunable TDFLs have been reported, where the tuning methods include optical devices such as fiber Bragg gratings [9, 10], volume Bragg gratings [11, 12], and tunable filters [13, 14]. In this sense, the reliability of the fiber optical loop mirror (FOLM) with high birefringence (Hi-Bi) fiber in the loop for wavelength tuning of Er and Er/Yb-doped fiber lasers operating in the 1.55 $\mu$m waveband has been demonstrated [15–20]. Different approaches of fiber lasers based on a two Hi-Bi FOLM configuration have been reported [21, 22].

However, to our knowledge, the use of two Hi-Bi FOLMs for wavelength selection and discrete tuning of TDFLs operating in the 2 $\mu$m wavelength region has not been reported yet. The main advantages of using the Hi-Bi FOLM for fiber laser-generated wavelength tuning lie in the selection of the wavelength and its tuning through a non-arbitrary method,

 

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# Laser Wavelength Estimation Method Based on a High-Birefringence Fiber Loop Mirror

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**Abstract:** A simple method for the estimation of the wavelength of a fiber laser system is proposed. The method is based on the use of a high-birefringence-fiber loop mirror (HBFLM). The HBFLM exhibits a periodic transmission/reflection spectrum whose spectral characteristics are determined by the length and temperature of the high-birefringence fiber (HBF). Then, by the previous characterization of the HBFLM spectral transmission response, the central wavelength of the generated laser line can be estimated. By using a photodetector, the wavelength of the laser line is estimated during an HBF temperature scanning by measuring the temperature at which the maximum transmitted power of the HBFLM is reached. The proposed method is demonstrated in a linear cavity tunable Er/Yb fiber laser. This method is a reliable and low-cost alternative for laser wavelength determination in short wavelength ranges without the use of specialized and expensive equipment.

**Keywords:** Wavelength meter; fiber lasers; fiber optical loop mirror; high-birefringence fiber

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## 1. Introduction

Nowadays, wavelength meters have extensive applications in optical instrumentation devices and systems such as optical filters, fiber lasers, fiber sensors, optical communications systems, and medical instruments. Particularly, determination of the emission wavelength of coherent light sources is required for many fiber laser applications which commonly require expensive equipments such as an optical spectrum analyzer (OSA), monochromators, and Fabry-Perot spectrum analyzers. In this sense, laser wavelength measurement methods and techniques have been increasing interests since the first wavelength measurement review reported by Solomakha and Toropov in 1977 [1].

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# Tunable Dual-Wavelength Thulium-Doped Fiber Laser Based on FBGs and a Hi-Bi FOLM

Manuel Durán-Sánchez, Ricardo I. Álvarez-Tamayo, Berenice Posada-Ramírez, Baldemar Ibarra-Escamilla, Evgeny A. Kuzin, José L. Cruz, and Miguel V. Andrés

***Abstract*— A tunable dual-wavelength thulium doped fiber laser is demonstrated experimentally. For the first time for the 2-$\mu$m wavelength band we propose the independent tuning of the generated laser lines based on fiber Bragg gratings and the use of a Hi-Bi fiber optic loop mirror for the fine adjustment of the cavity losses to obtain stable dual-wavelength operation. Dual-wavelength laser generation with the laser lines separation in the range from 0.3 to 6.5 nm is obtained. The laser emission exhibits an optical signal-to-noise ratio better than 56 dB. Improved stability with output power fluctuations less than 1 dB is observed in dual-wavelength generation with equal power of lines.**

***Index Terms*— Fiber lasers, fiber Bragg gratings, Sagnac interferometers, wavelength tuning.**

## I. Introduction

DUAL-WAVELENGTH fiber lasers based in Tm-doped fibers (TDF) operating at the 2-$\mu$m wavelength range have been received increasing attention in laser researches due to their great potential applications in optical communication, light detection and ranging (LIDAR), optical signal processing, microwave photonics, terahertz generation, and optical instrumentation. In this sense, dual-wavelength generation of all-fiber Tm-doped fiber lasers (TDFLs) has been increasingly achievable as 2 $\mu$m compatible fiber components become readily accessible. Recently, different dual-wavelength TDFLs approaches at the 2-$\mu$m wavelength band were reported. These configurations are based on fiber Bragg Gratings (FBG) [1]–[9], spatial mode beating effect [10]–[12], carbon nanotubes [13], photonic crystal fibers [14], and fiber interferometers [1], [15]–[17], among others. Liu *et al.* reported the single-polarization dual-wavelength generation of a TDFL based on a polarization maintaining (PM) FBG and a PM Fabry-Perot filter [1]. Zhou *et al.* proposed a stable dual-wavelength TDFL based on cascaded fiber Bragg gratings [6]. Soltanian *et al.* achieved stable dual-wavelength operation of a TDFL operating at 1.9 $\mu$m by using a 10 cm length of photonic crystal fiber [13]. Nevertheless, most of the previously reported dual-wavelength fiber lasers based on TDF exhibit laser emission with wavelengths below of 2 $\mu$m.

The main issue to achieve the stable dual-wavelength laser generation is the strong mode competition in the homogeneously broadened gain medium. In order to improve the stability of the simultaneously generated laser lines of TDFLs, different techniques for the intracavity losses adjustment have been proposed [1]–[13]. These techniques are based on the use of polarization controllers (PCs) [1]–[7], [10]–[13] and variable optical attenuators [8]–[9]. However, in the proposed techniques a rough and arbitrary adjustment of the intracavity losses is performed which reduces the repeatability and the stability of the dual-wavelength laser generation. From our previous research, the use of a fiber optical loop mirror with a high birefringence fiber in the loop (Hi-Bi FOLM) for the finely adjustment of the intracavity losses has been demonstrated as a reliable, non-arbitrary, and straightforward method to achieve the dual-wavelength generation in erbium-doped fiber lasers (EDFL) at the 1.55-$\mu$m waveband [18].

In this letter we propose for the first time, to our knowledge, a TDFL with the tunable dual-wavelength laser generation with wavelength above 2-$\mu$m with independent wavelengths tuning of both laser lines based on the use of tunable FBGs. We use a Hi-Bi FOLM for intracavity losses adjustment to achieve stable dual-wavelength laser emission.

The dual-wavelength laser emission with maximal wavelengths separations of 6.5 nm is obtained at the wavelengths of 2067 and 2073.5 nm. The stable dual-wavelength generation with equal powers is obtained with power fluctuations less than 1 dB and optical signal-to-noise ratio (OSNR) of ~56 dB.

## II. Experimental Setup

The schematic of the proposed configuration is shown in Fig. 1(a). A TDF with length of 10 m is used as a gain medium (TDF, Coractive SCF-TM-8/125). The TDF is pumped by a 1567 nm fiber laser through a 1550/2000 nm wavelength division multiplexer (WDM). An isolator (ISO) ensures unidirectional propagation from the pump source to the WDM to avoid parasitic lasing and back scattered light to the pumping source. The cavity is formed at one end by

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# Soliton molecules in self-mode-locked ring-cavity Er/Yb double-clad fiber laser

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**Abstract:** In this paper, generation of soliton molecules by a self-mode-locked Er/Yb double clad fiber laser is experimentally demonstrated. The optical spectrum of the bound solitons exhibits eight well defined peaks at ~1563 nm with high modulation depth. The corresponding autocorrelation measurement shows a fundamental trace with several narrow peaks, suggesting the presence of bound solitons. The obtained results demonstrate the reliability of our simple laser configuration for the formation of more robust soliton molecules as the pump power is increased. The soliton molecules exhibit repetition rate of 19.54 MHz and average power of 1.2 W, achieved with a pump power of ~4.8 W.

**Index Terms:** Fiber laser, mode-locked lasers, pulse propagation and temporal solitons.

## 1. Introduction

Passively mode-locked fiber lasers as simple and low-cost coherent sources with ultrashort pulsed emission are attractive for a wide range of applications including: fiber sensing, laser measurement, nonlinear optical properties of materials, spectroscopy, and optical communications, among others [1-4]. In order to obtain mode-locked laser operation in fiber lasers, different material-based fast saturable absorbers (SA) such as carbon nanotubes, semiconductor saturable absorber mirror, graphene, and topological insulators, have been extensively investigated. In this regard, another reliable technique to obtain mode-locked laser pulses, usually named self-mode-locking (SML), relies on the use of a long enough active fiber simultaneously as gain medium and as SA [5-8]. S. M. Zhang et al. [5] reported self-Q-switching (SQS) and mode-locking in an all fiber Erbium/Ytterbium (Er/Yb) co-doped fiber (EYDF) ring laser using a section of un-pumped EYDF as a saturable absorber; by combining the saturable absorption of the long length EYDF and a spectral filter, mode-locking pulses with duration of 26 ns were obtained. Brunet et al. in Ref. [6] describes a simple model for SML and sustained self-pulsing (SSP) transitions in Yb-doped fiber lasers, depending on the ratio between the absorbed pump power and the threshold absorbed pump power, where transitions from low-power SML to SSP and from SSP to high-power SML are obtained as the pump power is increased.

Once the pulsed operation of mode-locked lasers is stimulated by the saturable absorption effect, the dynamics of the laser cavity depends on a compromised balance between spectral filtering and nonlinearity, dispersion, and gain [9]. Then, a fiber laser serves as a complex dissipative system with fixed soliton solutions for plentiful pulsed states such as conventional solitons, soliton molecules [10-12], soliton rains [13], vector solitons [14], dissipative rogue waves [15], dissipative soliton resonance [16], noise-like pulses (NLP) [17], and symbiotic states [18]. Particularly, solitons molecules in fiber lasers have been of sustained theoretical and experimental studies during the last two decades [19-23]. Soliton molecules are stable structures formed by multiple solitons whose energy is proportional, but slightly different, to the sum of the single solitons involved, as it can be expected in a dissipative process. In B. A. Malomed firstly theoretically predicted that interactions of two solitons could lead to the formation of bund states when oscillating tail of solitons are slightly overlapped [24]. J. P.

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# Dual-wavelength thulium-doped fiber laser with separate wavelengths selection based on a two mmi filters configuration

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**Abstract**

Dual-wavelength laser emission of a ring cavity Tm-doped fiber laser with a separate wavelength selection of the simultaneously generated laser lines is experimentally demonstrated. A dual-wavelength laser operation is obtained by using two homemade multimode interference (MMI) filters with transmission peaks at the wavelengths of 1814.23 and 1872.15 nm, which are placed in a Mach Zehnder interferometer configuration for independent selection of the dual-wavelength generated laser lines. The selection of the shorter laser wavelength is achieved by submerging the MMI filter in different ethylene glycol/water mixtures, reaching a wavelength selection in the broad range of ~24 nm. The stability results of the simultaneously generated laser lines are also shown. The use of the proposed MMI filters as reliable spectral filters for dual-wavelength generation in all-fiber Tm-doped fiber laser systems is experimentally demonstrated.

Keywords: thulium-doped fiber laser, dual-wavelength lasers, wavelength filtering devices, multimode interference effect

(Some figures may appear in colour only in the online journal)

## 1. Introduction

Fiber lasers based on the use of a Tm-doped fiber (TDF) as a gain medium have been of great interest in recent years. The laser spectral emission around the 2 $\mu$m wavelength region exhibit 'eye-safe' radiation, which makes TDF lasers (TDFLs) attractive for their application in remote sensing, free-space communications, light detection and ranging, and spectroscopy gas sensing systems [1–3]. The strong absorption in water of wavelengths near to the 2 $\mu$m makes TDFLs useful for medical applications and surgical procedures [1, 4]. Furthermore, TDFLs offer potential applications for water vapour and carbon dioxide concentration detection in environmental research, and for polymeric materials processing [1].

 

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# All-fiber laser with simultaneous $Tm^{3+}$ passive *Q*-switched and $Ho^{3+}$ gain-switched operation

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**We experimentally demonstrate simultaneous $Tm^{3+}$ passive *Q*-switched (PQS) and $Ho^{3+}$ gain-switched laser operations at 1888.8 and 2021.2 nm, respectively, in a single-cavity all-fiber laser. The PQS operation of the $Tm^{3+}$ laser is based on the use of a high-concentration holmium-doped fiber as a fiber saturable absorber. Then the $Tm^{3+}$ laser emission is used as a pulsed pump source to achieve $Ho^{3+}$ gain-switched pulses. A high birefringence fiber optical loop mirror used as a spectral filter allows the tuning of both $Tm^{3+}$ and $Ho^{3+}$ laser emissions.** 

***OCIS codes:*** (140.3510) Lasers, fiber; (140.3070) Infrared and far-infrared lasers; (140.3538) Lasers, pulsed; (230.7408) Wavelength filtering devices; (140.5560) Pumping.

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Pulsed thulium-doped fiber (TDF) and holmium-doped fiber (HDF) lasers operating at wavelengths around 2 μm are of persistent interest because of a wide range of applications such as spectroscopy [1], light detection and ranging [2], laser surgery in medical treatment [3], and material processing [4]. The HDF lasers allow extension of the emission wavelength range to 2.1 μm, beyond the range reached by TDF lasers [5,6]. The TDF and HDF lasers offer advantages such as high reliability, compactness, maintenance-free operation, and robustness.

*Q*-switched fiber lasers generate high-energy pulses with duration in the nanosecond range. Particularly, passive *Q*-switched (PQS) lasers based on the use of a fiber saturable absorber (FSA) are simple and cost-effective devices. The FSA is commonly an unpumped segment of a rare-earth-doped fiber, where light absorption decreases with the increasing of the light intensity. The FSA is more effective when fibers with higher dopant concentrations and short lengths are used [7]. Different approaches of PQS lasers based on fibers doped with $Tm^{3+}$ or $Ho^{3+}$ used as FSAs have been reported [8–11].

Another reliable alternative for pulsed generation of fiber lasers is gain-switching (GS). In this technique, pulses with nanosecond duration are generated by using a pulsed pump source, without additional components [12]. In GS lasers, the pump source directly modulates the population inversion in the energy levels of the gain medium [13]. The HDF laser generation can be achieved with pump sources at wavelengths around 1950 nm [14], which can be easily generated by TDF lasers. Therefore, TDF lasers became reliable pump sources for HDF lasers. To the best of our knowledge, only three GS HDF lasers pumped by a pulsed TDF laser source have been reported in order to obtain pulsed laser generation at the 2.1 μm wavelength range [14–16]. In the cascaded laser configurations reported in Refs. [14] and [15], the HDF was pumped by the GS TDF laser which, in turn, was pumped by the 1.55 μm pulsed fiber laser. In Ref. [16] the HDF laser was pumped by the commercial *Q*-switched TDF laser. The fiber optical loop mirror (FOLM) with the high birefringence (Hi-Bi) fiber loop was shown to be the reliable spectral filter to achieve tunable single and dual-wavelength operations of fiber lasers [17,18]. The longest wavelength achieved in the TDF laser using the Hi-Bi FOLM was 1970 nm [18].

In this Letter, we experimentally demonstrate simultaneous $Tm^{3+}$ PQS and $Ho^{3+}$ GS laser operation of a single linear cavity fiber laser. The TDF is pumped by a continuous wave (CW) laser at 1567 nm. The segment of the high-concentration HDF acts as the FSA allowing PQS operation of the TDF laser. Then the pulses generated by the TDF laser are used as the pump for the same HDF, causing GS operation of the HDF laser. The Hi-Bi FOLM is used as the spectral filter for the tuning of both generated laser wavelengths.

The experimental setup of the proposed laser is shown in Fig. 1. The linear cavity consists of the 9 m long TDF (CorActive SCF-TM-8/125) which is pumped by A double-clad Er/Yb fiber laser at 1567 nm through a 1550/2000 nm wavelength division multiplexer. An optical isolator was used to avoid damage of the pump source. A 1 m long

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# Dissipative soliton resonance in a thulium-doped all-fiber laser operating at large anomalous dispersion regime

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**Abstract:** We experimentally demonstrate dissipative soliton resonance effect in a 173-m long passively mode-locked figure-eight thulium doped fiber laser with net anomalous dispersion. The duration of the wave-breaking-free pulse broadens with the increase of pump power. At maximum pump power of 4.5 W, square pulses were generated with duration of 85.18 ns, average output power of 245 mW, and pulse energy of 206 nJ, and repetition rate of 1.19 MHz.

**Index Terms:** Fiber laser, mode-locked lasers, pulse propagation, temporal solitons.

## 1. Introduction

Mode-locked thulium-doped fiber lasers (TDFLs) in the 2-µm wavelength band have been the subject of increasing interest for a wide range of applications in different research areas, such as microscopy [1], fiber amplifiers [2], nonlinear frequency conversion for mid-IR and THz generation [3], welding of polymeric materials [4] ,gas detection and analysis [5], among others. Passively mode-locked fiber lasers are considered very useful optical sources to generate stable and coherent ultrashort optical pulses. In TDFLs the generation of conventional solitons [6, 7], dissipative solitons [8, 9], and also the effect of the dissipative soliton resonance (DSR) [1, 2, 10-13] were demonstrated. Besides this, some quasi-stable dynamics such as the noise-like pulse (NLP) regime have been also reported [14, 15]. Several mode-locking mechanisms which include semiconductor saturable absorber mirror (SESAM) [8, 16], carbon nanotubes (CNTs) [17], graphene [7, 18], nonlinear polarization evolution (NPE) [14, 19, 20], nonlinear optical loop mirror (NOLM) [2, 14], and even combinations of them have been reported to perform a stable train of mode-locked optical pulses [21]. Saturable absorbers (SA) based on a nonlinear optical effect have the response time of around 5 fs. With combination of a nonlinear amplified fiber loop mirror (NALM) with a CNT SA, mode-locked pulses with short duration of 230 fs were reported [22]. Moreover, SESAM, CNTs and graphene exhibit some drawbacks including complex design for improving of damage threshold. On the other hand, most of the reported investigations on DSR effect have been done based on two different mechanisms: the use of NPE technique and a NOLM-based laser configuration.

In the framework of rectangular pulse generation, the DSR regime at the 2 µm wavelength region is relatively new. Theoretical studies of DSR based on the numerical solution of the complex cubic-quantic Ginsburg-Landau equation have been reported [23, 24]. DSR pulsed regime has unique properties such as long pulse duration, giant chirp and large pulse energy. In order to obtain high-power stable nanosecond-scale laser pulses, active Q-switching [25] and gain-switching [26] are commonly used techniques, however, these techniques require complex electronics for precise controlling of the output pulse characteristics, and exhibit lack of ability to operate in various pulse-shaping regimes. Conversely, mode-locked fiber lasers provide various pulse-shaping regimes based on nonlinear and dispersion mechanisms with less controlling components. In this regard, DSR promises to be an effective technique to generate rectangular-shape pulses in the nanosecond pulse duration range. DSR can be achieved in both anomalous and normal dispersion regimes [27, 28]. Most of the experimental results on DSR generation have been demonstrated for ytterbium [29-33], erbium [34-38], and erbium-ytterbium double clad fiber lasers [39-46]. However, a limited number of researches have been performed on DSR pulse operation in the 2 µm wavelength region. Y. Xu *et al.* reported an all-fiber figure-eight mode-locked thulium doped fiber laser with net-normal dispersion with pulse energy of 19.51 nJ and pulse width of 6.19 ns [10]. S. Tan *et al*. reported DSR in a TDFL with anomalous dispersion and pulse width of 438 ps for applications in microscopy [1]. J. Zhao *et al*. reported DSR in a thulium-doped double-clad fiber (TDCF) laser and demonstrated up to 100 W of average power, and pulse duration of

# Tunable Dual-Wavelength Thulium-Doped Fiber Laser Based on FBGs and a Hi-Bi FOLM

Manuel Durán-Sánchez, Ricardo I. Álvarez-Tamayo, Berenice Posada-Ramírez, Baldemar Ibarra-Escamilla, Evgeny A. Kuzin, José L. Cruz, and Miguel V. Andrés

***Abstract*— A tunable dual-wavelength thulium doped fiber laser is demonstrated experimentally. For the first time for the 2-$\mu$m wavelength band we propose the independent tuning of the generated laser lines based on fiber Bragg gratings and the use of a Hi-Bi fiber optic loop mirror for the fine adjustment of the cavity losses to obtain stable dual-wavelength operation. Dual-wavelength laser generation with the laser lines separation in the range from 0.3 to 6.5 nm is obtained. The laser emission exhibits an optical signal-to-noise ratio better than 56 dB. Improved stability with output power fluctuations less than 1 dB is observed in dual-wavelength generation with equal power of lines.**

***Index Terms*— Fiber lasers, fiber Bragg gratings, Sagnac interferometers, wavelength tuning.**

## I. Introduction

DUAL-WAVELENGTH fiber lasers based in Tm-doped fibers (TDF) operating at the 2-$\mu$m wavelength range have been received increasing attention in laser researches due to their great potential applications in optical communication, light detection and ranging (LIDAR), optical signal processing, microwave photonics, terahertz generation, and optical instrumentation. In this sense, dual-wavelength generation of all-fiber Tm-doped fiber lasers (TDFLs) has been increasingly achievable as 2 $\mu$m compatible fiber components become readily accessible. Recently, different dual-wavelength TDFLs approaches at the 2-$\mu$m wavelength band were reported. These configurations are based on fiber Bragg Gratings (FBG) [1]–[9], spatial mode beating effect [10]–[12], carbon nanotubes [13], photonic crystal fibers [14], and fiber interferometers [1], [15]–[17], among others. Liu *et al.* reported the single-polarization dual-wavelength generation of a TDFL based on a polarization maintaining (PM) FBG and a PM Fabry-Perot filter [1]. Zhou *et al.* proposed a stable dual-wavelength TDFL based on cascaded fiber Bragg gratings [6]. Soltanian *et al.* achieved stable dual-wavelength operation of a TDFL operating at 1.9 $\mu$m by using a 10 cm length of photonic crystal fiber [13]. Nevertheless, most of the previously reported dual-wavelength fiber lasers based on TDF exhibit laser emission with wavelengths below of 2 $\mu$m.

The main issue to achieve the stable dual-wavelength laser generation is the strong mode competition in the homogeneously broadened gain medium. In order to improve the stability of the simultaneously generated laser lines of TDFLs, different techniques for the intracavity losses adjustment have been proposed [1]–[13]. These techniques are based on the use of polarization controllers (PCs) [1]–[7], [10]–[13] and variable optical attenuators [8]–[9]. However, in the proposed techniques a rough and arbitrary adjustment of the intracavity losses is performed which reduces the repeatability and the stability of the dual-wavelength laser generation. From our previous research, the use of a fiber optical loop mirror with a high birefringence fiber in the loop (Hi-Bi FOLM) for the finely adjustment of the intracavity losses has been demonstrated as a reliable, non-arbitrary, and straightforward method to achieve the dual-wavelength generation in erbium-doped fiber lasers (EDFL) at the 1.55-$\mu$m waveband [18].

In this letter we propose for the first time, to our knowledge, a TDFL with the tunable dual-wavelength laser generation with wavelength above 2-$\mu$m with independent wavelengths tuning of both laser lines based on the use of tunable FBGs. We use a Hi-Bi FOLM for intracavity losses adjustment to achieve stable dual-wavelength laser emission.

The dual-wavelength laser emission with maximal wavelengths separations of 6.5 nm is obtained at the wavelengths of 2067 and 2073.5 nm. The stable dual-wavelength generation with equal powers is obtained with power fluctuations less than 1 dB and optical signal-to-noise ratio (OSNR) of ~56 dB.

## II. Experimental Setup

The schematic of the proposed configuration is shown in Fig. 1(a). A TDF with length of 10 m is used as a gain medium (TDF, Coractive SCF-TM-8/125). The TDF is pumped by a 1567 nm fiber laser through a 1550/2000 nm wavelength division multiplexer (WDM). An isolator (ISO) ensures unidirectional propagation from the pump source to the WDM to avoid parasitic lasing and back scattered light to the pumping source. The cavity is formed at one end by

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