RESEARCH ARTICLE

Isolator-free, widely tunable thulium/holmium fiber laser

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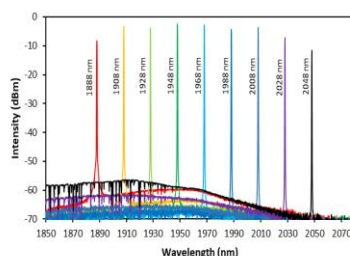
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Graphical abstract

Abstract

An isolator-free thulium/holmium-doped fiber laser with a broadly tunable wavelength output is proposed and demonstrated for the first time. A theta resonator configuration is implemented in order to produce rectification of lasing direction without the need for an optical isolator, thus, making it a more cost-effective setup in comparison to the conventional ring resonator. Over 160 nm of wavelength tunability can be generated, which covers a huge range of the two-micron region starting from 1888 nm up to a maximum of 2048 nm. The laser exhibits excellent wavelength control with its short-range wavelength tuning capability, whereby the shortest tuning spacing obtainable is as small as ~0.1 nm. The tunable laser peaks maintain a strong optical-signal-to-noise (OSNR) value for the whole tuning range, reaching more than 60 dB, also a full-width half-maximum (FWHM) value less than ~0.2 nm with a maximum output power of 6.82 mW. The isolator-free cavity indicates a significant improvement in the slope efficiency of the laser in comparison to a ring cavity setup with similar components. The proposed laser would have substantial use as a laser seed for application in sensing and spectroscopy.

Keywords: Tunable fiber laser, thulium, holmium, theta cavity, isolator-free

INTRODUCTION

In recent years, research in fiber lasers has shifted its focus from the common 1530 - 1565 nm band by the Erbium-doped Fiber Amplifier (EDFA) to develop other noteworthy wavelength bands such as the two-micron region. This spectral band which is at the range of 1700 – 2400 nm is associated with the Thulium-doped Fiber Amplifier (TDFA), which has been progressively studied to be used for future optical communications [1, 2]. Nonetheless, the true attraction of this unique spectral band is that it is enriched with strong absorption lines for water molecules and atmospheric gases [3, 4]. This characteristic of the wavelength band allows it to be utilized for a multitude of applications in sensing [5, 9-11] and spectroscopy [12-14], especially by configuring it into a tunable two-micron laser source [5-8].

Generally, a fiber ring cavity is the preferred configuration for rare-earth-doped fiber lasers [9, 10]. This type of cavity is essentially a ring resonator which employs an optical isolator to ensure unidirectional propagation of light in order to generate single-frequency lasing operation. However, a ~2 µm optical isolators is an expensive component due to the eccentricity of the two-micron wavelength band in comparison to the conventional telecommunication band. The optical isolators also operate in a narrow operating bandwidth, usually around tens of nanometers. Thus, optical isolators may not be the best choice for wide-tuning operations [11].

Quite recently, a paper by Kharitonov *et. al* have proposed an unconventional isolator-free theta cavity for two-micron lasers [11-13]. The theta resonator is essentially a combination of two ring resonators which will fundamentally suppress a certain propagation direction. In other words, this cavity does not require an optical isolator for rectifying the lasing path thus, providing a cost-effective and reliable solution to generate a widely tunable dual-wavelength two-micron fiber laser [11, 12, 14].

This work proposes and demonstrates an isolator-free, widely tunable two-micron fiber laser. The proposed laser uses a theta resonator configuration with a pair of 2 X 2, 3-dB couplers to enable an S-shaped feedback. In order to achieve a tunable laser emission within the two-micron wavelength range, a tunable bandpass filter is employed as the tuning agent together with a Thulium/Holmium-doped fiber (THDF) as the preferred gain medium. THDF is principally a co-doped fiber which exploits the pump absorption of Tm^{3+} ions at 1.55 µm to generate light at ~1.8-2.0 µm. The emitted light will consequently excite the Ho^{3+} ions at $^5I_7 \rightarrow {}^5I_8$ and allow for emission at 1.95 – 2.1 µm [3, 15]. To the best of the author's knowledge, this is the first demonstration of a tunable wavelength Thulium/Holmium-doped Fiber Laser (THDFL) implementing a theta resonator configuration. The proposed laser has a promising use in the application of sensing and spectroscopy.

FUNDAMENTAL PRINCIPLES OF THETA RESONATOR

The theta cavity provides rectification of lasing direction by introducing non-reciprocal cavity loss in such a way that it completely suppresses light propagation at a specific direction. The non-reciprocal signal loss is achieved by constructing an S-shaped feedback within a ring cavity, creating a theta-like pattern. Fig. 1 describes a simple model of the theta resonator [11]. The model considers a ring resonator with a lumped gain G and loss L with two directional couplers (DC1 and DC2) creating an S-shaped feedback which ultimately dictates the behavior of the light propagation within the cavity.
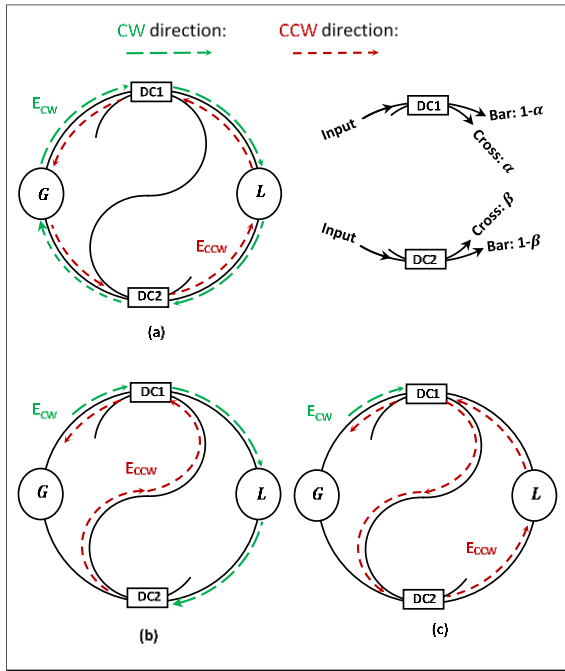
Fig. 1 Basic model of theta resonator (a) the main CW and CCW paths. (b) First possible rectifying signal from CW to CCW. (c) Second possible rectifying path from CW.

The light signal propagates in two directions; clockwise and counter-clockwise. E_{CW} and E_{CCW} represents the intensity of light propagating in each direction.. The cross-coupling ratio of DC1 and DC2 are depicted as α and β respectively, meanwhile $(1 - \alpha)$ and $(1 - \beta)$ are terms referring to the coupling output into the main ring path. These terms are further illustrated as in Fig. 1. E_{CW} and E_{CCW} mainly circulate along the outer ring as in Fig. 1 (a). However, the connected cross output of DC1 and DC2 reroutes the E_{CW} to the E_{CCW} path as shown in (Fig. 1 (b) and (c)). The $n^{th} + 1$ round trip for E_{CCW} and E_{CW} based on Fig. 1 can be expressed by Equations (1) and (2) respectively:

$$E_{CCW,n}G_{CCW}(1 - \alpha)L(1 - \beta) + E_{CW,n}, \; G_{CW}(1 - \beta)\alpha\beta L +$$

$$E_{CW,n}G_{CW}\alpha\beta(1 - \beta)L = E_{CCW,n+1} \quad (1)$$

$$E_{CW,n}G_{CW}(1 - \alpha)L(1 - \beta) = E_{CW,n+1} \quad (2)$$

G_{CW} and G_{CCW} represents the gain acquired by the light (E_{CW} and E_{CCW}) as it passes by the clockwise or anticlockwise direction. The first term for Equation (1) is the main path for E_{CCW} as in Fig. 1 (a), while the second and the third term describes the conversion of the E_{CW} to the E_{CCW} path as in Fig. 1 (b) and (c). Meanwhile, Equation (2) describes the main path for E_{CW} as described in Fig. 1(a). A glance at Equation (1) and (2) foreshadows that E_{CCW} will repress E_{CW} since a significant portion of E_{CW} diverts to the E_{CCW} path and not otherwise.

In a steady state regime, $E_{CW,n+1} = E_{CW,n} = E_{CW}$ and similarly to E_{CCW}. We can then rewrite (2) as:

$$[(1 - \alpha)(1 - \beta)L)]^{-1} = G_{CW} \quad (3)$$

Then, by substituting (3) into (1), the following expression is obtained:

$$E_{CCW}\frac{G_{CCW}}{G_{CW}} + 2E_{CW}\frac{\alpha\beta}{1 - \beta} = E_{CCW} \quad (4)$$

By assuming steady-state condition, $G_{CCW} = G_{CW}$, hence, canceling out the E_{CCW} part in (4), which will also lead to $E_{CW} = 0$. In other words, the CCW signal prevails over the CW component. Based on (4), since $E_{CW} = 0$, this means that at the steady-state condition, the CW signal will always be suppressed regardless of the coupling ratio.

However, based on previous investigation, this is not the case as the coupling ratio will affect the performance of the laser [11, 16].
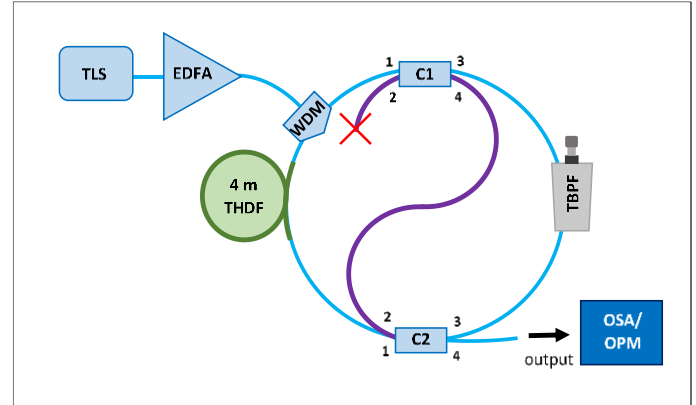
EXPERIMENTAL SETUP

Fig. 2 Isolator free tunable THDFL theta cavity setup.

A wavelength-tunable THDFL operating in the two-micron region using a theta resonator configuration is shown in Fig. 2. The THDFL cavity utilizes a single-mode Coractive TH512 Thulium/Holmium-doped Fiber (THDF) as the gain medium to provide emission within the two-micron wavelength band. The gain medium is a 4-meter-long fiber with a numerical aperture (NA) of 0.16 and a core absorption of ~21 dBm at 1.55 µm. The laser pump for the cavity comprises of a C-band tunable light source (TLS) that is set at a center wavelength of 1.55 µm which is then amplified using a Keopsys Erbium-doped Fiber Amplifier (EDFA) capable of reaching a high output power within the range of watts. The pump is integrated into the cavity by using a 1550/2050 nm Haphit wavelength division multiplexer (WDM). Wide wavelength tunability is achieved by employing a tunable bandpass filter (TBPF) from Agiltron which functions as the wavelength-selective feedback mechanism. The TBPF is a compact and rugged device that filters out specific wavelength in order to allow excellent wavelength tuning in the two-micron region.

The rectification of feedback signal is done with the absence of optical isolators. This is executed by deploying a pair of 3-dB 2 X 2 couplers (C1 and C2), whereby their respective cross-outputs are connected to form an S-shaped feedback. The S-shaped feedback forms the theta-like shape which introduces non-reciprocal losses in order to achieve light rectification. C1 and C2 are connected via their cross-outputs that is port 4 and port 2 respectively. Port 2 of C1 is unused, thus, it is terminated. C1 is placed inside the cavity by connecting the port 1 to the 2000 nm port of the WDM and port 3 to the TBPF. On the other hand, C2 is placed between the THDF and TBPF that is respectively connected to port 1 and port 3 of C2. Finally, the output of the laser is taken from port 4 of C2 which is taken for the measurement of the wavelength spectrum by using a Yokogawa AQ6375 Optical Spectrum Analyzer (OSA) and the average output power is by using a Thorlabs S302C optical power meter (OPM).

RESULTS AND DISCUSSION

A Thulium/Holmium-doped fiber laser (THDFL) working in the two-micron region is generated by employing the configuration as proposed in Fig. 2. Fig. 3 describes the single lasing operation with a center wavelength λ_c of 1968 nm that is generated at a threshold of 532 mW with an output power of 2.71 mW. The laser itself has a strong optical-signal-to-noise ratio (OSNR) of ~65 dB with a full-width half-maximum (FWHM) of ~0.18 nm. By adjusting the tuning knob of the TBPF, wide wavelength tunability is achieved from 1888 nm to 2048 nm, with 20 nm spacing giving a total of 160 nm of tuning range as described in Fig. 4. The whole lasing spectrum maintains an OSNR above ~60 dB with an average FWHM of less than ~0.2 nm.
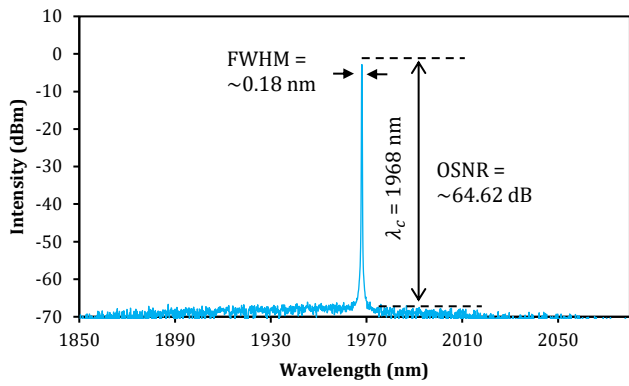
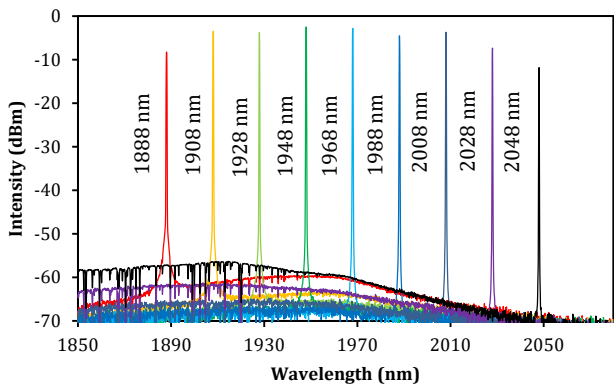**Fig. 3** Laser emission at 1968 nm from the THDFL theta cavity setup.

Fig. 4 Full tuning spectrum of the THDFL from 1888 nm to 2048 nm.

Fig. 5 Wavelength stability of the THDFL tested for one-hour operation.

Fig. 6 Small tuning capability of the THDFL.

Fig. 7 Comparison of the slope efficiency between the theta cavity and the ring cavity design.

In order to test the two-micron filtering reliability of the TBPF, a wavelength stability test is done. The optical trace of the laser for each wavelength as in Fig. 4 is taken at ten minute interval for a total of one-hour operation. Then, the respective center wavelength of each laser trace is measured and plotted as in Fig. 5. The configured laser shows excellent wavelength stability whereby no mode-hopping can be observed for the whole one-hour operation. Additionally, the laser shows minor wavelength drift at an average of ~0.03 nm from the center wavelength.

The tunable THDFL setup also demonstrates considerably good wavelength-control as it is capable to perform short wavelength-tuning with spacing as small as ~0.1 nm as described in Fig. 6. Finally, the isolator-free, theta cavity THDFL setup is compared with a conventional ring cavity laser. A straightforward ring cavity is constructed whereby the coupler C1 in Fig. 2 is replaced with a 2050 nm isolator. Since both laser setup utilizes a common TBPF, the laser output should have similar wavelength tunability, OSNR, and linewidth. Therefore, only the output power to the input power slope efficiency of the setup is compared. The comparison wavelength chosen is at 1968 nm output which is at the center of the wavelength tuning spectrum as in Fig. 4. Fig. 7 shows that the efficiency of the proposed theta cavity design significantly outperforms the conventional ring design. The optical isolator works by allowing unidirectional transmission of light within the fiber by Faraday effect. However, the optical isolator suffers from having a small operating bandwidth. In this work, the only available optical isolator at hand has an operating wavelength of 2050 ± 20 nm. At 1968 nm, the optical isolator in use is inherently unsuitable for the lasing wavelength, thus, explaining the huge difference between the efficiency of the lasers in study. If the operating bandwidth of the isolator matches the laser wavelength in study, the characteristics of the laser design should be similar as previously investigated by Kharitonov et. al [11].Therefore, this shows that in the absence of a suitable optical isolator, the theta cavity design is a much better alternative.
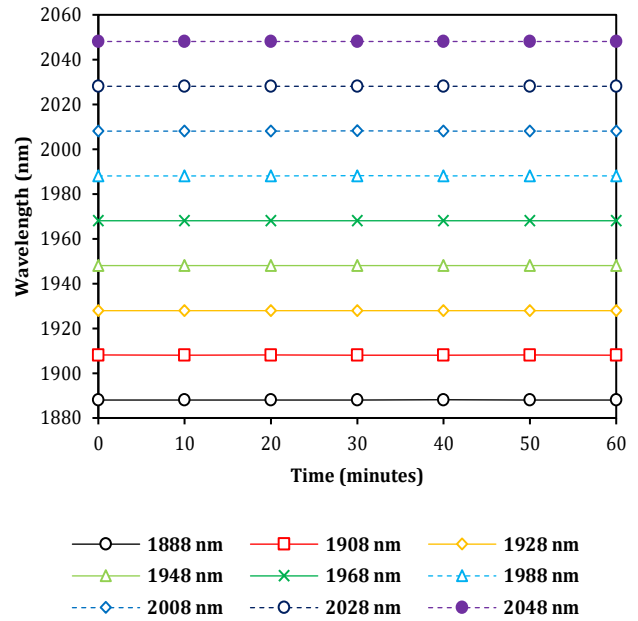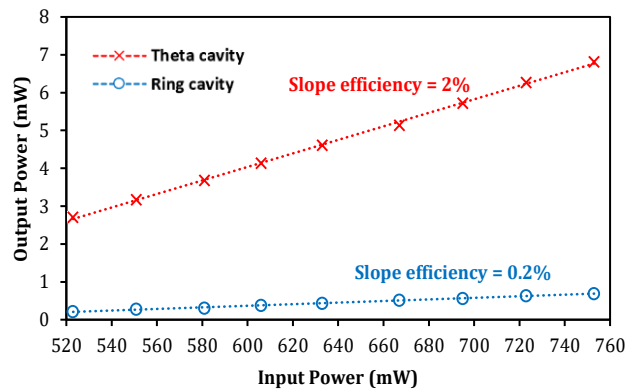
It is also noted from previous literature that the efficiency of the laser varies with the chosen cross-coupling ratios [11,16]. In term of OSNR, FWHM and wavelength-tuning capability, the isolator-free cavity design is not underperformed in comparison to our previous work [9]. However, the efficiency of the laser could be improved provided that better optical components and SM 2000 fiber is used for the cavity design. Nevertheless, this tunable THDFL configuration has a cost-effective design with promising potential as a tunable laser seed especially for sensing application.

CONCLUSION

A tunable two-micron Thulium/Holmium-doped fiber laser implementing a theta cavity is proposed and demonstrated in this work. The theta cavity enables a cost-effective isolator-free design whereby the rectification of lasing direction is dictated by the S-shaped feedback of the couplers. The tunable wavelength signal is produced by making use of a TBPF which is capable of tuning capability up to ~160 nm with controllable spacing as small as ~0.1 nm. The generated two-micron laser has excellent stability with an OSNR value of more than ~60 dB and FWHM of less than ~0.2 nm. The proposed TDWFL has a significant potential to be used mainly for sensing applications.

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