IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 6, Number 5, October 2014

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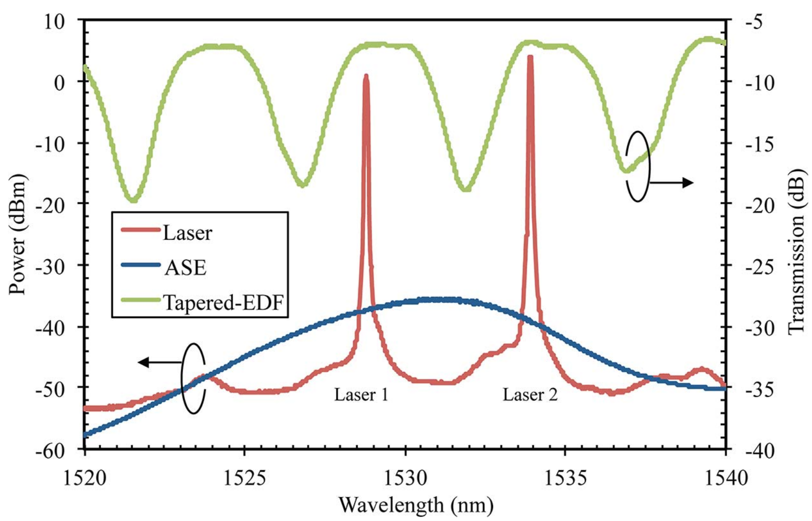

DOI: 10.1109/JPHOT.2014.2361642
1943-0655

Tapered-EDF-Based Mach–Zehnder Interferometer for Dual-Wavelength Fiber Laser

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DOI: 10.1109/JPHOT.2014.2361642

Manuscript received August 8, 2014; revised September 30, 2014; accepted September 30, 2014. Date of publication October 13, 2014; date of current version October 23, 2014. This work was supported in part by the Universiti Putra Malaysia and the Ministry of Education, Malaysia, under Research Grant #05-02-12-2024RU, in part by the University of Malaya, under Research Grant UM.C/625/1/HIR/MOHE/SCI/01, and in part by the three-year scholarship of the Academic Training Scheme for Institutions of Higher Education, Ministry of Education, Malaysia. Corresponding author: M. A. Mahdi (e-mail: mam@upm.edu.my).

Abstract: An all-fiber comb filter using a tapered-erbium-doped fiber in a Mach–Zehnder interferometer structure is presented. The free spectral range, extinction ratio, bandwidth, and interference pattern of the comb filter can be shaped by controlling the taper waist length and the length of up and down taper transition regions. By varying the taper waist length from 5 to 25 mm, the free spectral range changes from 14.7 to 1.0 nm, and the linewidth varies from 3.3 to 0.3 nm, respectively. We demonstrate a tunable dual-wavelength laser by using the tapered-erbium-doped fiber as a gain medium as well as a wavelength-selective element. The laser can be tuned at a resolution of 0.2 nm with a side-mode suppression ratio of up to 46.88 dB and a linewidth of 0.09 nm.

Index Terms: Tapered fiber, Mach–Zehnder interferometer, fiber laser.

1. Introduction

A single fiber laser cavity producing multiple wavelengths is highly desirable for the reduction of cost, size, and improvement of system integration in optical fiber communication networks. Although the use of nonlinear effects has attracted a lot of research interest in this area [1], [2], it is significantly simpler to produce a multiwavelength source using a single gain medium in combination with wavelength-selective elements. In order to select specific multiple lasing wavelengths, a wavelength-selective comb filter is typically included in the laser cavity [3]–[5].

There are many methods reported for all-fiber comb filters, such as the Fabry Perot filter [2], Lyot filter [6], fiber grating [7], Sagnac loop interferometer [8], and Mach–Zehnder interferometer (MZI) [9]–[11]. Among these, MZI may have notable advantages such as broad wavelength operation range [12], insensitivity to environmental changes, ease of fabrication at relatively low

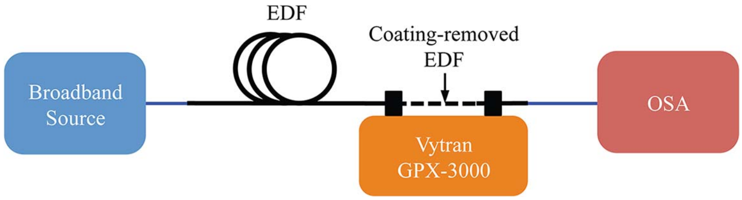

Fig. 1. Setup for fabrication of tapered-EDF.

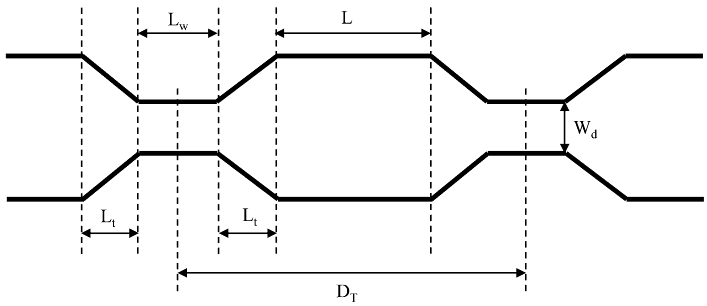

Fig. 2. Schematic diagram of two taper regions connected in series to form an MZI filter.

cost as well as high reliability and stability [13]. Recently, MZI based on tapered-fiber structure has received remarkable attention due to its benefits such as simple and low-cost fabrication, easy tuning method [10], relatively wide tuning range as well as high stability [12]. However, typical MZI structure is made using conventional optical fibers, which works independently from the amplifying medium. These two elements can be integrated together in the laser cavity by forming the MZI using the active gain medium itself.

In this work, we present an experimental investigation on the characterization of tapered-erbium-doped fiber (EDF) as a comb filter in multiwavelength fiber laser. We impart the effects of varying the taper waist length to the spectral profile, free spectral range (FSR), extinction ratio, bandwidth and interference pattern of the spectrum. It is worth to note that a single taper is an interferometer on its own. Additionally, by cascading the two tapered-EDFs, it is possible to achieve wider tuning range due to wider FSR and larger spectral modulation depth [13]. By using EDF as a gain medium as well as a wavelength-selective element, we are able to demonstrate a tunable dual-wavelength erbium-doped fiber laser (EDFL).

2. Tapered-EDF Fabrication and Characterization

The experimental setup for the tapered-EDF is depicted in Fig. 1. In this experiment, a 3 m long EDF having core and cladding diameters of 6 and 125 μm respectively, is tapered at approximately 20 cm from the fiber end. The other end is connected to a broadband source, which is capable of providing a broad spectrum output ranging from 1520 to 1620 nm. The total output power of the broadband source is fixed at 13.1 dBm. The output end of the EDF is connected to an optical spectrum analyzer (OSA) to observe the change in spectral profile before and after the EDF is tapered.

The EDF is tapered using a Vytran GPX-3000 series optical fiber processing workstation. A graphite filament is used as the heating element. It is stable and able to produce intense heat that can be precisely controlled and varied from room temperature to 3000 °C. The taper profile can be set according to desired parameters. In this experiment, the taper waist diameter (W_d) is fixed at 5 μm, up and down taper lengths (L_t) are similarly set at 5 mm while taper waist length (L_w) is varied from 5 to 25 mm. The purpose of this experiment is to observe the effect of varying taper waist length to the output spectrum profile. The interferometer length (L) is unchanged at 200 mm as depicted in Fig. 2. In addition to this, the separation between

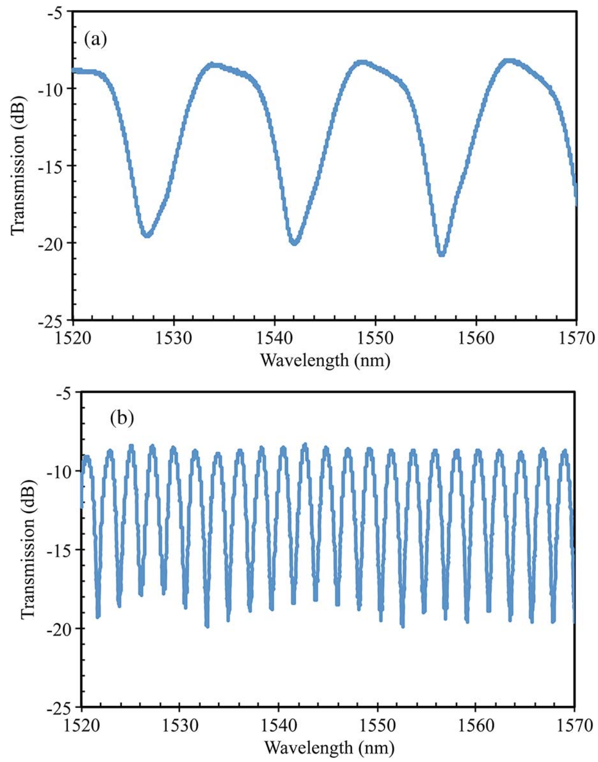

Fig. 3. Transmission characteristics by varying taper waist length. (a) 5 mm and (b) 15 mm.

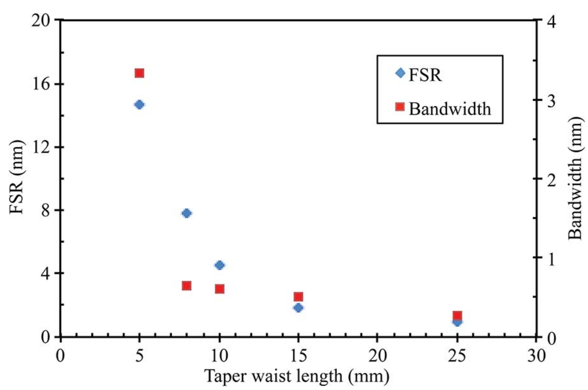

Fig. 4. FSR and bandwidth dependence on taper waist length.

tapered sections (D_T) is also changed proportionally to the taper waist length, in this case from 215 to 235 mm.

The transmission spectra for variations of the tapered-EDF waist length are depicted in Fig. 3. It is obtained by subtracting the spectrum from the source before and after the tapering process. Comb-like spectral profile is observed with varying FSR in an inversely proportional manner to the waist length. As illustrated in Fig. 3(a), the FSR is 14.7 nm for 5 mm waist length and reduced to 1.85 nm when the waist length is increased to 15 mm as shown in Fig. 3(b). In addition, the 3-dB spectral bandwidth changes in the same manner, with the values measured at 3.3 and 0.3 nm for the waist length of 5 and 15 mm, respectively. In order to properly observe this effect, the FSR and spectral bandwidth relation to the waist length is presented in Fig. 4.

It is worth to note that the waist diameter (W_d) and transition region length (L_t) are kept constant at 5 μm and 5 mm, respectively.

The FSR of the interference fringes between the fundamental core mode and the mth-order cladding mode of the EDF in the vicinity of signal wavelength, λ_s is approximately given as

$$FSR = \frac{\lambda_s^2}{(n_{core\text{-}eff} - n_{clad\text{-}eff}^m)L} \tag{1}$$

where L is the length of EDF, and $n_{core\text{-}eff}$, $n_{clad\text{-}eff}^m$ are the effective index of the fundamental core mode and that of the mth-order cladding mode, respectively [14]. The effective refractive index difference between the core mode and the cladding mode gives rise to the differential phase shift and results in multiple interferences, which are observable as fringes pattern in the transmission spectra shown in Fig. 3.

The coupling between modes along the tapered fiber occurs in the transition region and not in the waist region. Under this situation, the mode amplitude remains constant but the phases continue to accumulate. As a result, the leaky modes in the cladding propagate with their respective phases and due to the difference in phase velocities, the modes beat to each other. For each pair of modes j and m, the beat length, Z_{Bjm} corresponds to the distance after which the two modes regain their initial phase. Thus

$$Z_{Bjm} = \frac{2\pi}{|\beta_j - \beta_m|} \tag{2}$$

where β_j and β_m are the propagation constant of modes j and m correspondingly [14]. The total field results from the superposition of all the amplitude of these modes and its evolution along the fiber depend on the beating between each pair of modes. Thus, the length of the waist region allows the accumulated phase of the respective modes to be adjusted before they couple back to the core mode. Since the coupling depends on this accumulated phase, the waist length does significantly affect the final output [14].

It is crucial to note that each taper is an individual interferometer, where the period of interference pattern is determined mainly by the waist length. Depending on the application, the waist length and transition region length should be optimized to obtain the desired interference shape.

3. Fiber Laser Performance

The experimental setup of the proposed EDFL is shown in Fig. 5. This configuration is constructed by a section of backward-pumped 3 m long EDF with in-line two-taper MZI filter, a 1480 nm laser diode (LD), a 1480/1550 wavelength-selective coupler (WSC), a 3 dB (50 : 50) coupler and an isolator to reduce unwanted back reflection signals in the cavity and to ensure a counterclockwise oscillation in the ring cavity. The output is monitored by an OSA at the 50% arm of the coupler. The fabricated tapered-EDF MZI filter is then embedded in the ring configuration to generate multiwavelength lasers. In this case, we fabricated a taper with slightly larger waist for ease of handling purposes. The tapered fiber profile is 10 μm, 5 mm and 15 mm for the waist diameter, Trl and waist length correspondingly. The interferometer length is fixed at 20 cm. The transmission spectrum for this taper profile is depicted in Fig. 6. At Trl of 5 mm, the fringe visibility is observed for wavelength between 1520 and 1620 nm. The extinction ratio for this region ranges between 9 to 11 dB.

The output of the EDFL measured at 50% arm of the coupler is a dual-wavelength laser as shown in Fig. 6. The two laser lines are obtained at pump power of 200 mW; Laser 1 at 1528.778 nm and Laser 2 at 1533.877 nm. The laser lines have side-mode suppression ratio (SMSR) of 45.55 dB and 46.88 dB and linewidth of 0.09 nm and 0.094 nm for Laser 1 and Laser 2, respectively.

In this situation, the lasing occurs around 1530 nm, which is the peak erbium emission region in the case of high population inversion as indicated by the amplified spontaneous emission

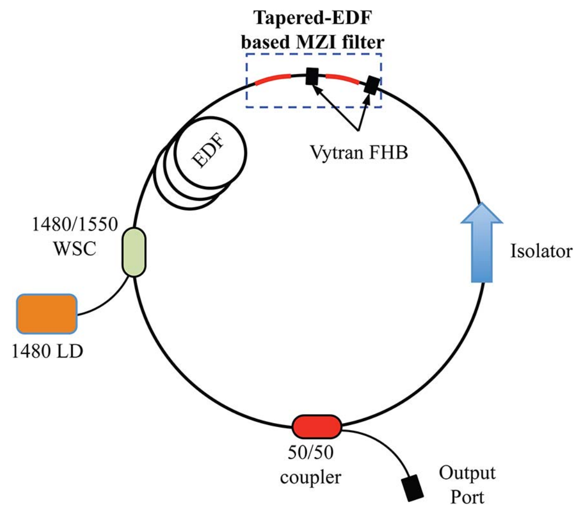

Fig. 5. Setup to achieve multiwavelength laser using ring cavity EDFL with in-line two-tapered-EDFs (MZI) filter.

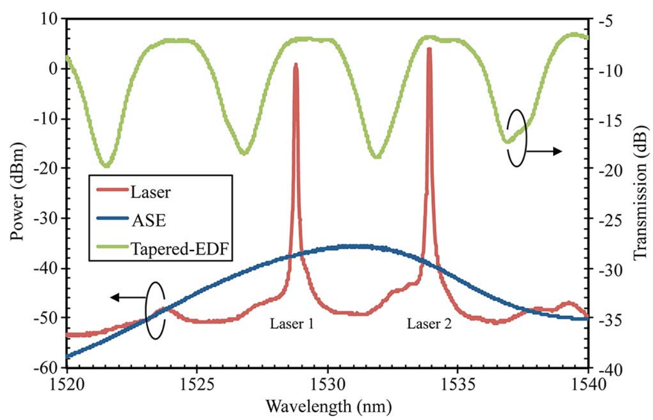

Fig. 6. The transmission spectrum of the tapered EDF MZI filter (green), dual-wavelength laser using tapered-EDF MZI filter at pump power = 200 mW (red), and ASE spectrum at pump power = 200 mW (blue).

(ASE) spectrum in Fig. 6. The MZI acts as a comb filter and lasing can only take place at the intensity transmission peaks of the interferometer. It is observed that the lasing occurs at a point where there is a net gain between erbium gain and comb filter loss, which can be observed in Fig. 6.

In order to study the stability of the lasing wavelength at room temperature, 15 consecutive scans of the system output were carried out with 5 minutes step for each scan and the results are depicted in Fig. 7. From Fig. 7(a), the maximum peak power fluctuation was less than 0.38 dB and 0.47 dB for Laser 1 and Laser 2 respectively. In addition to this, the measured wavelength drift is less than 0.19 nm and 0.15 nm for Laser 1 and Laser 2, respectively, as shown in Fig. 7(b). It is important to mention that the tapered-EDF has been annealed for 24 hours at 120 °C to remove internal mechanical stresses introduced during the tapering process and hence, improves the stability of the MZI structure [7]. The influence of surrounding temperature can be further mitigated by fabricating this tapered-EDF with a thermal package.

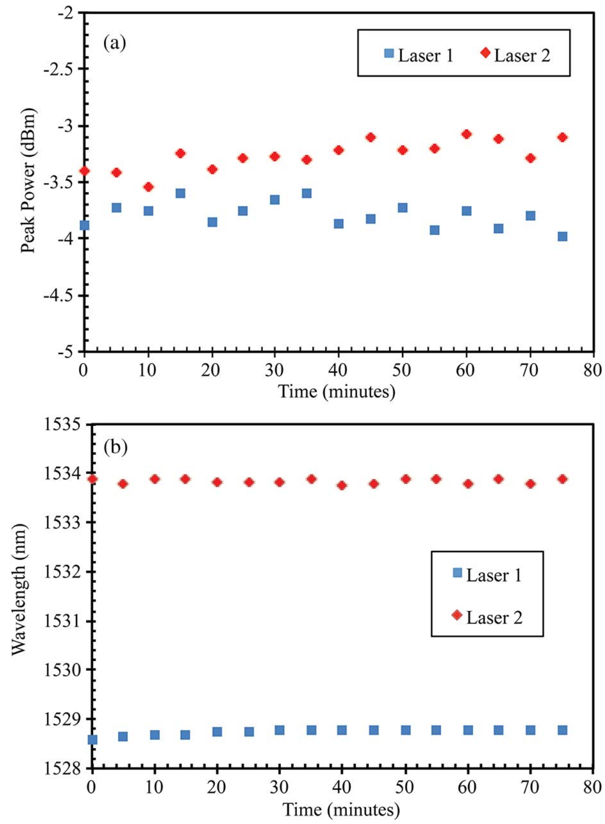

Fig. 7. Stability measurement of the dual-wavelength laser in terms of (a) peak power and (b) wavelength drift.

To verify the wavelength stability independence from the pump current, the dual-wavelength laser is plotted against the variation of pump current as represented in Fig. 8(a). The lasing effect will take place when the pump power is sufficiently high and the energy of the system has reached the lasing threshold. In this case, the pump threshold is 200 mA (51.7 mW) for Laser 1. It is observed that above the lasing threshold, both lasers are stable with wavelength variations less than 1.0 nm when the pump current is tuned from 300 mA (81 mW) to 800 mA (218 mW), as illustrated in Fig. 8(b).

To investigate the relative intensity noise (RIN) properties of the laser, an experimental measurement was performed using GwINSTEK GSP-830 electrical spectrum analyzer (ESA) which can scan laser frequency up to 3 GHz. The intensity noise was measured using u^2t photonics photodetector with 50 Ω load and a bandwidth of around 50 GHz and responsivity of 0.65 A/W at 1530 nm. At pump power of 110 mW, the measured RIN is$-$50.18 dB/Hz. At maximum pump power (218 mW), the RIN is $-$54.05 dB/Hz. The RIN keeps decreasing with increasing pump power, which is in agreement with the investigation performed by [15] utilizing noise analysis based on noise transfer function derived by using full quantum theory. Although a low value of RIN is desirable, fiber laser, in particular EDFL exhibits large amount of intensity noise that mostly comprises of vacuum noise from the output coupling, pump source intensity noise and the spontaneous emission of Er^{3+} ions from upper state to ground level [15]. Furthermore, a low concentration of Er^{3+} ions and randomly phased back reflection into the laser cavity may give rise to laser instability and hence an increase in RIN [16].

The tunability of the proposed dual-laser based on tapered-EDF MZI filter is demonstrated in Fig. 9(a). The first taper region of the two concatenated taper MZI is bent by moving one of the ends closer to the other end in transverse direction. The movement is controlled by using

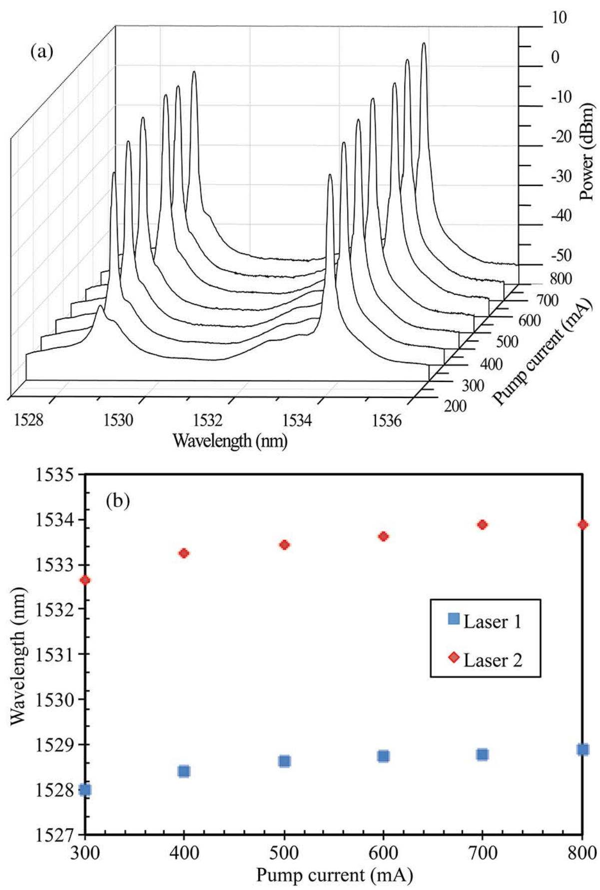

Fig. 8. (a) Dual-wavelength laser with the variations of pump current and (b) wavelength with respect to pump current (mA).

Vytran's fiber holding block (FHB) that can accurately move in nanometer scale. The FHB is moved from 0 (initial) to 12.0 nm at 2.0 nm step size. As the taper moved from the initial location to the next stage location, the taper bending angle increases.

As the taper is bent, more cladding modes are excited thus changing the coupling coefficient of different cladding modes [12], [13]. Fig. 9(b) illustrates the laser wavelength tunability for each stage location with respect to the stage initial location (0). Without bending, the wavelength of the laser output is as above-mentioned Laser 1 and Laser 2. As the taper is bent (bending angle is increased), the wavelength is tuned from 1528.778 nm to 1528.998 nm for Laser 1 and from 1533.877 nm to 1534.096 nm for Laser 2. The SMSR within this range is maintained at about 40 dB for both lasers. As the taper is bent further, the wavelength for both lasers will be tuned further to the longer wavelength. However, the SMSR deteriorates with increasing wavelength as reflected by Laser 2 in Fig. 9(a). This is due to net gain imbalance attributed to the erbium gain profile and cavity loss. Fig. 9(b) shows that the tuning step is linearly proportional with the stage location at approximately 0.2 nm tuning step. By using this method, the proposed dual-wavelength laser can be tuned easily.

4. Conclusion

In conclusion, we have successfully demonstrated the functionality of tapered-EDF as a comb filter in MZI structure. The FSR and bandwidth of the filter can be easily varied by changing the waist length of the tapered region. With this setup, we are able to achieve a tunable

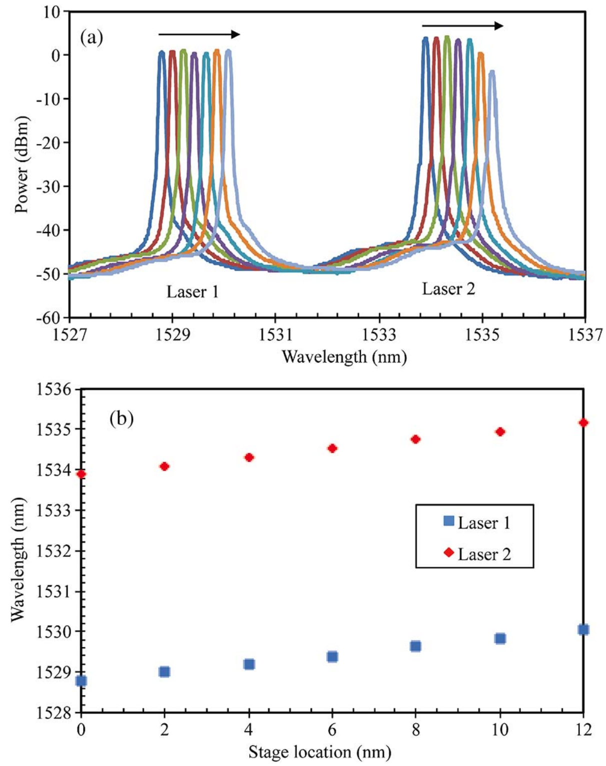

Fig. 9. (a) Spectrum of dual-wavelength laser tunability by bending mechanism. (b) Wavelength tuning characteristics with respect to stage location.

dual-wavelength laser with tuning step as low as 0.2 nm and extinction ratio of up to 45.55 dB and 46.88 dB with linewidth of 0.09 nm and 0.094 nm for Laser 1 and Laser 2, respectively. The utilization of tapered-EDF as a gain medium and comb filter provides an integrated solution to simplify fiber laser setups.

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