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A highly stable and switchable dual-wavelength laser using coupled microfiber Mach-Zehnder interferometer as an optical filter

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ABSTRACT

The generation and switching of dual-wavelength laser based on compact coupled microfiber Mach-Zehnder interferometer (CM-MZI) is reported. The CM-MZI is constructed by overlapping two portions of a single tapered optical fiber which has a diameter of 9 μm as to create multi-mode interference and also to produce spatial mode beating as to suppress mode competition in the homogeneous gain medium. The system is able to generate a dual-wavelength laser output that can be switched with the aid of the polarization rotation technique. Four dual-wavelength oscillation pairs are obtained from the interference fringe peaks of the CM-MZI comb filter with a switched channel spacing of 1.5 nm, 3.0 nm, and 6.0 nm. The wavelength spacing is stable at different pump powers. The lasing wavelength has a 3-dB linewidth of about 30 pm and peak-to-floor ration of about 55 dB at a pump power of 38 mW.

1. Introduction

Over the past decade, all-fiber based stable dual-wavelength fiber laser sources have created interest primarily due to their potential applications in optical communication, microwave and Terahertz generation [1–4] as well as in fiber sensing systems [5,6]. The ability to tune the generated dual-wavelength output gives a significant advantage to the afore-mentioned applications [7,8].

The capability to generate a stable dual-wavelength output is dependent on multiple factors that influence the overall characteristics of the optical cavity. Among these factors, the use of a suitable gain medium is a very important point to consider, in terms of its saturated output power, a flat gain spectrum and also low polarization dependent gain [9]. In this regard, Erbium-doped fibers (EDFs) have long been the mainstay of gain media in fiber systems, in particular due to their adherence to the afore-mentioned characteristics. However, amplifiers and lasers based on EDFs have an inherent limitation, in which strong mode competition is present in closely spaced wavelengths due to the EDF's homogenously broadened linewidth. In order to overcome this limitation, the nonlinear polarization rotation (NPR) effect in the fiber ring cavity can be exploited to induce intensity dependent loss which can suppress the mode competition in the gain medium [10–12]. Alternatively, the use of optical filters in the ring cavity can be a solution towards suppressing mode competition and to realize stable multi-wavelength fiber lasers.

To date, various techniques have been explored to achieve dual-wavelength lasing output using different kind of optical fiber elements and configurations where each technique has its own advantage and disadvantage over other technique. For instance, the distributed-feedback EDF laser based on special fiber grating structure designs [13–15], distributed feedback (DFB) polymer lasers, [16], Rayleigh backscattering in fiber [17], reconstruction equivalent chirp technique [18], cooperation of polarization-maintaining erbium-doped fiber (PM-EDF) with polarization controller (PC) [19], or by introducing a comb filter in the laser cavity [20]. However, most of these systems suffer from significant limitations due to their high fabrication cost, as well as requiring many components or optical devices to generate the desired output, thus adding bulk and complexity to the laser cavity. Optical microfibers in particular have attracted substantial interest due to their associated exciting properties, such as three-dimensional assembly with small size, immunity to electromagnetic interference, large evanescent field and strong confinement of the signal light, that are advantageous for a wide range of applications including lasing systems, sensing devices and application in the area of nonlinear optics [21–23]. In this regard, optical filters based on microfiber interferometer and resonators structures are commonly investigated for the generation of multi wavelength laser outputs. These include microfiber knot resonators (MKRs) [24,25], microfiber Sagnac loop mirrors [26] and inline microfiber interferometer [27–29]. In addition, these structures allow for the coupling of modes

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between the core and cladding–air layers as to create interference and serve as a wavelength selective filter in the ring laser cavity. However, such microfiber filters are unable to be reconfigured since the microfiber itself has knotted and twisted in a circular compact geometry, in which this makes the device unable to be disconnected until it breaks. The same applies to the inline microfiber interferometer devices where they actually fabricated by either making dual tapering regions on a single microfiber, or by tapering the microfiber within an abrupt angle, making them insufficient to fulfil all technical demands within the field of telecommunications.

In this work, a highly stabilized switchable dual-wavelength EDF laser is demonstrated using a reconfigurable compact coupled microfiber Mach-Zehnder interferometer (CM-MZI) as a comb filter. The CM-MZI is constructed by overlapping two microfiber arms that were initially fabricated from a single 9-μm tapered fiber by the flame-drawing technique. The microfiber arms both have different path lengths. The CM-MZI allows input light to separate into two waves and then recombined back at the output, creating mode interference. Four sets of dual-wavelength lasing oscillation extracted from the peaks of the interference fringes of the CM-MZI comb filter with a switched channel spacing of 1.5 nm, 3.0 nm, and 6.0 nm are achieved using polarization rotation technique. This is due to beating in the spatial mode of multi-mode interference in which this enhances suppression mode competition of the homogeneous gain medium inter-modal interference that suppressed the mode competition. The CM-MZI as a filter has the key advantage of simplicity in design with low cost. The CM-MZI also offers the unique advantages of being erasable and reconfigurable as compared to the aforementioned optical filters by simply splitting the coupled arms using a cleaved standard optical fiber, thus gives high flexibility of refabrication with a desire of changing in the path length difference (PLD) between two coupled arms. Furthermore, since the coupled arms of the CM-MZI are formed by evanescent coupling and sustained by van der Waals and electrostatic forces, the PLD can also easily be changed by applying a small pressure to move the contact points using micromanipulation. With such feature the wavelength spacing of the comb filter can be controlled. However, the performance of the CM-MZI will vary after reconfiguration due to the changes in the coupling parameters.

2. Fabrication and theory of CM-MZI

The CM-MZI is constructed from two portions of tapered adiabatic silica microfibers, which are derived from laterally tapering a standard telecom optical single mode fiber (SMF) using a home-made Computer Numeric Control (CNC) controlled flame-brush tapering machine. The machine has good control over the length and speed of tapering and flame movement, giving more control over the shape of the microfiber. The machine uses a flame sourced from separately supplied oxygen and butane gas. Both oxygen and butane gas pressures are regulated at ~5 psi. The flame has a temperature estimated to be between 1100 and 1400 °C. The mixing of both gases takes place in the torch chamber and the mixture is supplied to a ~3 mm sized pin-point flame at the torch tip that has core diameter of 200 μm.

Initially the tapered microfiber is fabricated utilizing the flame-drawing technique, in which a standard SMFs with its coating removed is heated to soften the fiber. The softened fiber is then gently pulled so that the overall diameter of the fiber is reduced to about 9 μm over a length of 6 cm. At this point, the tapered fiber remains a single, unbroken fiber. During the fabrication process, one end of the fiber is connected to a broadband amplified spontaneous emission (ASE) source, with the other end connected to an optical spectrum analyzer (OSA) providing in-situ measurement of the loss induced in the fiber during the fabrication process. The fabricated microfiber is then carefully cut using a clean scissors into two arms that are approximately equal in length to each other. One of the microfiber arms is lifted, and the other arm is coupled to the first arm by the help of surface attraction forces van der Waals / electrostatic forces [30], such that a half-loop is formed using the two arms of tapered fiber as illustrated in Fig. 1.

As shown in Fig. 1 the CM-MZI has two coupling regions between microfiber parts where at this coupling regions the evanescent field of the signals propagating along the fiber can interact. The distance between the coupling regions is measured to be 1.5 cm. As can be seen from the Fig. 1, the incident light wave E_0 from un-tapered left side of SMF at the first coupling region which can split into two waves, E_1 and E_2. The E_1 and E_2 waves propagate through Arms 1 and 2 respectively. After travelling through the respective microfiber arm, waves E_1 and E_2 will experience phase changes of $\beta_1 L_1$ and $\beta_2 L_2$ before recombining at the second coupling region. The recombined wave at the output can be described as E_3. By assuming $\beta = \beta_1 = \beta_2$ the transmission wave can be expressed as [31];

$$T = \frac{E_3}{E_0} = j\left[k_2^{\frac{1}{2}}(1-k_1)^{\frac{1}{2}}e^{j\beta L_1} + k_1^{1/2}(1-k_2)^{1/2}e^{j\beta L_2}\right] \qquad (1)$$

where k_1 and k_2 are the intensity coupling ratio at the first and second coupling region respectively. The PLD between two microfiber arms can be expressed as ΔL which is equal to L_1 - L_2, thus the transmission wave resulting into:

$$T = j\left[k_2^{1/2}(1-k_1)^{1/2}e^{j\beta\Delta L} + k_1^{1/2}(1-k_2)^{1/2}\right]e^{j\beta L_2} \qquad (2)$$

The difference in the path length of the microfiber arms create a phase difference which leads to an optical phase shift. This is a result of the delay between the signals propagating in Arms 1 and 2 and thus results in interference fringes when they recombine at the second coupling region before being guided to the OSA through the output port of SMF. Fig. 2 shows the ASE spectrum response of the CM-MZI has a PLD of 1.11 mm with insertion loss of about 15 dB.

As it can see from Fig. 2, a clear interference pattern with free spectral range (FSR) of ~1.5 nm is observed within a wavelength region of 1549 nm. The FSR of the CM-MZI can be expressed as:

$$\Delta\lambda = \lambda^2/(\Delta L n_{eff}) \qquad (3)$$

where λ and n_{eff} are the operating wavelength and effective refractive index respectively.

Fig. 3(a) and (b) show the image captures of the CM-MZI.

Fig. 3(a) shows the image capture of the constructed CM-MZI hold on tapering stage. The red shine in Fig. 3(a) is the injected red light source into the CM-MZI for greater visibility. Fig. 3(b) shows the microscope image for the left side coupled region. It must be noted that performance of the proposed CM-MZI filter can be limited as it sensitive to the air turbulence and it should be either placed in an environment free of air turbulence or packaged. The performance of the CM-MZI is affected by the air turbulence as it can sway the bent arm of the interferometer and thus the coupling coefficient and PLD between the arms might be affected. As a consequence, the interferometer produces volatile output transmission.

3. Experimental setup

The proposed ring laser cavity with total length of 25 m is shown in Fig. 4, where the set-up consists of 3-meter-long Metrogain-12 (M12) EDF as the gain medium and its output connected to a 1550 nm isolator to ensure unidirectional propagation of light and prevents any unwanted effects such as spatial hole burning in the EDF, which may affect the stability of the system.