Dual-wavelength fiber laser operating above 2 μm based on cascaded single-mode-multimode-single-mode fiber structures

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Abstract: A stable dual-wavelength Tm3+:Ho3+ co-doped fiber laser operating above 2 μm based on cascaded single-mode-multimode-single-mode (SMS) fiber structures is proposed and experimentally demonstrated. Based on the theoretical analysis of the transmission properties of the SMS fiber structure, two cascaded SMS fiber devices with different multimode fiber (MMF) lengths were used in our laser system, where one acted as a long-pass filter to suppress the competitive laser below 2 μm, and the other worked as band-pass filter to select the specific operating wavelengths of the laser. Dual-wavelength operation of the fiber laser at 202.8 and 2016.1 nm has been achieved in the experiment with a signal to noise ratio up to 50 dB.

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References and links

1. Introduction

Fiber lasers around 2 μm, corresponding to characteristic absorption lines of liquid water, greenhouse gases and some other chemical compounds, have attracted intense attention over the past few years [1-3]. Due to their great potential in practical applications such as differential absorption lidar systems (DIALs), medical diagnosis and terahertz difference frequency generation [4-6], dual-wavelength operation of fiber lasers in this regime has been achieved with several approaches. For example, using two volume Bragg gratings (VBGs) [7], Wang et al. realized a tunable dual-wavelength thulium (Tm3+) doped fiber laser (TDFL), where the operating wavelength can be tuned independently with the incident angle of each VBG. Polarization hole burning enhanced by high-birefringence FBG was observed and applied by Peng et al. to generate a switchable dual-wavelength TDFL at 1.94 μm [8]. Ma et al. proposed a dual-wavelength TDFL incorporating a Sagnac loop mirror and tunable operation was achieved with a polarization controller inside the cavity [9]. Recently, Soltanian et al. demonstrated a dual-wavelength fiber laser operating at 1.9 μm with a photonic crystal fiber-based Mach-Zehnder interferometer [10].

However, most previously reported dual-wavelength fiber lasers are based on Tm3+-doped fibers and their operating wavelengths are below 2 μm. It is more attractive to develop a compact dual-wavelength fiber laser operating above 2 μm because in this regime the atmosphere has relatively high transparency and some gases like CO2 have stronger absorption, which facilitates numerous applications including coherent Doppler wind lidars, CO2 DIAL systems and other gas sensing systems. Because the unit gain of Tm3+-doped silica fiber decreases significantly with increased wavelength above 2 μm, it is difficult to achieve a dual-wavelength fiber laser in this regime. Ho3+-doped fiber or Tm3+:Ho3+ co-doped fiber is a good candidate for dual-wavelength laser operation above 2 μm because it can provide high gain through the transition between energy levels 5I7 and 5I8 [11].

The self-imaging effect of multimode interference (MMI) in multimode fiber (MMF) has been extensively investigated with the single-mode-multimode-single-mode (SMS) fiber structure. Different devices and lasers based on the SMS fiber structure have been experimentally demonstrated by several groups for various applications such as a wavelength
tunable fiber lens [12], all-fiber Q-switched fiber lasers [13], Bessel-like beam generators [14], high power multimode fiber lasers and amplifiers with single-transverse mode output [15], and all-fiber filters [16,17]. Most recently, the SMS fiber structure has been used to achieve multiple-wavelength operation of a Tm$^{3+}$-doped fiber laser around 1.9 μm [18].

In this paper, we present the investigation of the transmission spectrum of an SMS fiber device in the 2 μm wavelength region and the demonstration of a dual-wavelength fiber laser operating above 2 μm by using two cascaded SMS fiber structures. Here, one SMS structure with a short MMF length acts as a high-pass filter to suppress the laser at shorter wavelengths, and the other SMS structure with long multimode fiber length works as a band-pass filter to select specific lasing wavelengths. In the experiment, dual-wavelength operation of a Tm$^{3+}$:Ho$^{3+}$ codoped fiber laser at 2002.8 and 2016.1 nm has been achieved with an SNR up to 50 dB. Stable operation was verified by monitoring the power fluctuations at both wavelengths for 30 minutes.

2. Theoretical analysis of the transmission characteristics of the SMS fiber structure

The SMS fiber structure consists of a piece of MMF spliced with two segments of single mode fiber (SMF). Due to the circularly symmetric characteristics of the fiber, the source light within the SMF is assumed to have a Gaussian-shaped field distribution of $E_{n}(r,0)$. Under the circumstance of ideal axis-alignment and in the linear polarization approximation, only the $LP_{0n}$ modes, $\psi_{n}(r)$, are strongly excited when the single-mode light is launched into the MMF, and the field distribution at a length $L$ can be expressed as [19]

$$E_{MMF}(r,L) = \sum_{n=1}^{N} c_{n} \cdot \psi_{n}(r) \cdot \exp(i\beta_{n}L).$$

(1)

where $c_{n}$ and $\beta_{n}$ are the excitation coefficient and propagation constant of the $n$th linearly polarized mode in the MMF, respectively.

When the light reaches the interface between the MMF and the output SMF, which is identical to the input fiber, it will be coupled to the core and cladding modes of the output SMF. As the light propagates in the output SMF, only the power coupled to the core mode survives and that coupled to the cladding modes will leak to the outer jacket eventually. Therefore, the transmission of the SMS structure can be written as [20]

$$T(L) = 10\log_{10}\left( \frac{\int_{0}^{\infty} E_{MMF}(r,L)E_{s}(r)r \, dr}{\int_{0}^{\infty} E_{s}(r)L \, dr} \right).$$

(2)

For an SMS fiber structure with fixed multimode fiber length, the wavelength interval for self-imaging $\Delta\lambda_{im,n}$ can be expressed with the formula shown below [15]:

$$\Delta\lambda_{im,n} = \frac{1}{L} \left[ \frac{d\Delta n_{eff,n}}{d\lambda} - \frac{1}{\lambda} \Delta n_{eff,n} \right].$$

(3)

where $\Delta n_{eff,n} = (\beta_{n} - \beta_{0})\lambda / 2\pi = n_{eff,n} - n_{eff,0}$ is the effective refractive index difference between $n$th excited mode of the multimode fiber and fundamental mode in the single mode fiber.

According to the equation above, one can conclude qualitatively that the wavelength interval for self-imaging decreases with the multimode fiber length. Furthermore, the same conclusion can be drawn for the wavelength spacing of the transmission spectrum of the SMS fiber structure. To definitively verify this conclusion, we simulated the transmission spectra of
SMS structure with the MMF used in the experiment (Thorlabs AFS105/125Y): the core and cladding diameters were 105 and 125 μm, respectively; the core refractive index of the fiber is 1.4385 at a wavelength around 2 μm. SMF-28 fiber was chosen as the single mode fiber with a core diameter of 8.3 μm.

The transmission spectra of the SMS fiber structure for different MMF lengths were simulated and are shown in Fig. 1. When the length of MMF in the SMS fiber structure increases from 50 to 200 mm, the wavelength spacing of the transmission peaks decreases gradually, which indicates that an SMS fiber structure with longer MMF length can be employed in a fiber laser system to act as a wavelength selector, as presented in Fig. 1(c), achieving dual-wavelength and even multi-wavelength operation. Furthermore, for an SMS structure with a short MMF length, the transmission bandwidth becomes very broad and the transmission spectrum is flat, as shown in Fig. 1(a). As defined in Ref. 15, an SMS fiber structure with a fixed MMF length has the best self-imaging quality at the highest transmission peak, where the quasi-reproduction of the input field occurs. As the wavelength deviates from the transmission peak, the phase differences between excited modes at the end of MMF increase and consequently the self-imaging quality decreases [15], which induces increased transmission loss. This can be understood intuitively by looking at the transmission spectrum of a 50 mm long MMF SMS device in Fig. 1(a), where the loss increases with the wavelength decreasing from 2050 to 2000 nm. Accordingly, an SMS structure having shorter MMF length can work as a long-pass filter to suppress the competitive laser at shorter wavelengths. Therefore, as illustrated by the spectra shown in Fig.1 (d), we can combine the two SMS devices with MMF lengths of 50 and 200 mm in a cascaded fashion in a Tm³⁺:Ho³⁺ co-doped fiber laser to achieve dual-wavelength operation above 2 μm.

![Figure 1. Transmission spectra of the SMS fiber structure for different multimode fiber lengths: (a) L_{MMF}=50 mm; (b) L_{MMF}=100 mm; (c) L_{MMF}=200 mm; (d) Comparison of the transmission spectra of the SMS structure for L_{MMF}=50 mm and 200 mm.](image-url)
3. Experimental setup and results

The experimental schematic of the dual-wavelength fiber laser is shown in Fig. 2. A piece of Tm$^{3+}$:Ho$^{3+}$ co-doped fiber (CorActive TH512) was chosen as the gain medium. The Tm$^{3+}$:Ho$^{3+}$ co-doped fiber has core and cladding diameters of 9 and 125 μm, respectively, associated with a core absorption coefficient of ~23 dB/m at 1570 nm, and was pumped by a homemade 1570 nm CW fiber laser through a 1570/2000 nm wavelength division multiplexer (WDM). An isolator was spliced in after the active fiber to enable the light to have unidirectional propagation in the ring cavity. 30% of the laser power was extracted from the ring cavity by a 30/70 fiber coupler to monitor the spectrum. The SMS fiber devices used in the experiment were fabricated by splicing two SMF-28 fibers to a piece of MMF.

![Figure 2. Schematic of the dual-wavelength fiber laser based on cascaded SMS fiber devices.](image)

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![Figure 3. Lasing spectra of the fiber laser under different Tm:Ho co-doped fiber lengths without SMS devices in the cavity.](image)

Figure 3. Lasing spectra of the fiber laser under different Tm:Ho co-doped fiber lengths without SMS devices in the cavity.

Generally, the active fiber length is chosen for sufficient pump absorption and thus 1 m of Tm$^{3+}$:Ho$^{3+}$ co-doped fiber can absorb the pump with a coefficient of 23 dB. However, since the lasing wavelength red-shifts with the fiber length due to the re-absorption process [21], longer active fiber length should be used in the experiment to achieve laser operation above 2
μm. The operating wavelength of the free-running ring laser (without the two SMS structures) with various different Tm³⁺:Ho³⁺ co-doped fiber lengths was investigated at a launched pump power of 1.5 W. As shown in Fig. 3, a longer active fiber enables the Tm³⁺:Ho³⁺ codoped fiber laser to operate at a longer wavelength and operation above 2000 nm was obtained with a 7-m gain fiber, which makes it possible to achieve dual-wavelength operation at long wavelengths. Therefore, a 7-m Tm:Ho co-doped fiber was used in the dual-wavelength fiber laser.

![Image of measured transmission spectra](image)

**Figure 4.** Measured transmission spectra of the SMS1, SMS2 as well as cascaded SMS fiber devices.

The transmission spectra of the two cascaded SMS fiber devices were measured with a supercontinuum source (NKT SuperK COMPACT) and are shown in Fig. 4. One SMS (named SMS1) with an MMF length of 4.5 cm acted as a long-pass filter to suppress competitive lasing around 1950 nm. The other SMS (named SMS2) with a 20.3-cm MMF worked as band-pass filter to select the specific operating wavelengths. It should be pointed out that the transmission spectra we obtained here were not associated with perfect self-imaging. The loss of the SMS device is about 6 dB, which significantly limits the efficiency of the fiber laser. Reducing the propagation loss of the SMS devices by improve the self-imaging is currently under way for power scaling of the dual-wavelength fiber laser above 2 μm.

When only the SMS2 device was used in the ring cavity, in addition to a laser at 2021.2 nm, another laser at a shorter wavelength of 1982.4 nm was observed as shown in Fig. 5(b). This short wavelength lasing usually cannot be suppressed by adjusting the transmission peak of the SMS2 with different MMF lengths because an SMS fiber device with a long multimode fiber length is associated with a relatively small transmission peak spacing and small loss differences between these peaks, which is essential for dual-wavelength or multi-wavelength operation. The transmission spectrum of the SMS1 with 4.5-cm MMF length is shown in Fig. 5(a), which shows that the SMS1 can be used as a long-pass filter to allow the laser above 2 μm to operate and suppress lasing below 2 μm. Therefore, we put the two SMS fiber devices in cascaded fashion into the ring cavity to achieve dual-wavelength operation above 2 μm. The transmission spectrum of the cascaded SMS device was measured and is shown in Fig. 4, which is the combined transmission of the two SMS fiber devices, i.e. the wavelength space between two transmission peaks is small while the transmission loss of the light below 2 μm is significantly increased.
When the two SMS fiber devices were incorporated into the ring cavity, the output spectrum of the fiber laser was measured with an optical spectrum analyzer (OSA, YOKOGAWA AQ6375). Single wavelength operation of the laser at 2002.8 nm was obtained at a pump power of 480 mW. When the pump power increased to 1.1 W, dual wavelength operation with the second laser wavelength at 2016.1 nm was achieved, as shown in Fig. 6(a). However, dual-wavelength operation was not stable at this pump level, especially for the long wavelength laser at 2016.1 nm. The stability of the dual-wavelength operation was improved when the pump power was increased. Figure 7(b) shows the dual-wavelength operation of the fiber laser at a pump power of 1.5 W. The SNRs at both wavelengths were larger than 50 dB. The 3-dB bandwidth at the wavelengths of 2002.8 and 2016.1 nm were measured to be 0.21 and 0.06 nm, respectively. In order to know the individual output powers corresponding to the two wavelengths, we integrated their spectra separately and calculate their power ratio. When the pump power was 1.5 W, the output powers for the two laser wavelengths were 2.4 and 0.8 mW, respectively, which is due to their different thresholds. Dual-wavelength operation with equal output power can be achieved by tailoring the transmission spectrum of the cascaded SMS device.

Figure 5. (a) Transmission spectrum of SMS1 and the corresponding lasing spectrum with it in the ring cavity. (b) Transmission spectrum of SMS2 and the corresponding lasing spectrum with it in the ring cavity.

Figure 6. (a) Spectra of single wavelength operation of the fiber laser at a pump power of 480 mW (black line) and dual-wavelength operation at a pump power of 1.1 W (red line), and the transmission spectrum of the cascaded SMS fiber device. (b) Spectrum of stable dual-wavelength operation of the fiber laser at a pump power of 1.5 W.
To investigate the stability of the output power at the two laser wavelengths, we monitored the output spectra of the fiber laser at a pump power of 1.5 W for 30 minutes. The optical spectra of the laser measured at a time intervals of 5 minutes are shown in Fig. 7(a). Figure 7(b) shows the output power stability of the two lasers at 2002.8 and 2016.1 nm in 30 minutes. Our experimental results show that stable dual-wavelength operation of a Tm$^{3+}$:Ho$^{3+}$ codoped fiber laser above 2 μm can be achieved by using a cascaded SMS fiber device. However, the output power of the dual-wavelength fiber laser is only 4.9 mW at a launched pump power of 2 W and the slope efficiency was measured to be around 0.3%. In addition to the relatively small gain of the Tm$^{3+}$:Ho$^{3+}$ co-doped fiber above 2 μm, the low output power and efficiency are mainly attributed to high cavity loss, including the large loss of the silica fiber and fiber devices at a wavelength above 2 μm and the propagation losses of the SMS fiber devices. For instance, the insertion losses of the WDM and isolator at the laser wavelengths were measured to be 0.9 and 1 dB, respectively. The propagation loss of the cascaded SMS fiber device was measured to be 8.5 and 7 dB at the two laser wavelengths of 2002.8 and 2016.1 nm, respectively, as shown in Fig. 6(a). The efficiency of the dual-wavelength fiber laser will be improved by reducing the losses of the two SMS devices through optimization of the parameters of multimode fiber (core diameter, fiber length, etc.).

4. Conclusions

In conclusion, a dual-wavelength fiber laser operating above 2 μm has been proposed and demonstrated by using two cascaded SMS fiber devices. One SMS fiber device with a short (4.5 cm) multimode fiber acted as a long-pass filter to suppress the competitive laser below 2 μm and the other one with a long (20.3 cm) multimode fiber worked as a band-pass filter to select the specific lasing wavelengths. A dual-wavelength fiber laser operating at 2002.8 and 2016.1 nm has been achieved with an SNR > 50 dB. Stable operation of the dual-wavelength operation has been verified by monitoring the individual output power at the two wavelengths for half an hour. The efficiency of this dual-wavelength fiber laser can be significantly improved by optimizing the SMS fiber devices.

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