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2.07 μm 光纤激光在弱湍流条件下的传输特性研究

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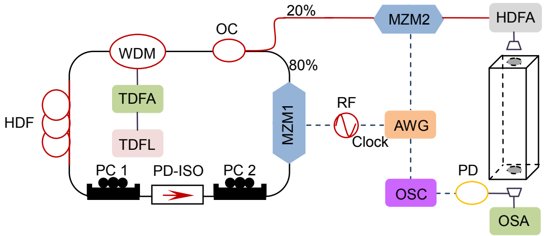

摘要：本文报道了一种 2.07 μm 波段可调谐主动锁模光纤激光并在室内模拟大气湍流条件下进行传输特性研究。增益介质为 1.5 m 长的掺钬光纤，主动锁模通过 $LiNbO_3$ 强度调制器在腔内引入周期强度调制实现。腔内引入非线性偏振旋转效应实现波长 2058.4 nm~2078.6 nm 可调谐。实验获得了稳定的基频锁模脉冲和 10 阶，24 阶，48 阶谐波锁模脉冲，对应频谱信噪比为 66.79 dB、61.37 dB、54.82 dB 和 49.66 dB。锁模脉冲经过数字调制后在实验室内大气湍流模拟池中进行传输，分别获得了 ΔT 为 70 ℃，140 ℃和 210 ℃时三种湍流强度和背对背条件下的眼图；与背对背条件相比，在 ΔT=210 ℃时光信噪比降低了 9.14 dB。

关键词：光纤激光器；主动锁模；空间激光通信；大气湍流

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Propagation characteristics of 2.07 μm fiber laser in weak turbulence condition

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Abstract: We demonstrate an actively mode-locked holmium-doped fiber laser with a central wavelength of 2.07 μm, and the propagation characteristics under weak turbulent condition are analyzed. A segment of 1.5 m holmium-doped fiber is used as gain medium. Actively mode-locked can be realized by introducing periodic intensity modulation into cavity through $LiNbO_3$ intensity modulator. The nonlinear polarization rotation effect is introduced into the cavity to realize the tunable wavelength of 2058.4 nm~2078.6 nm. Stable mode-locked pulses with fundamental frequency and 10th, 24th, 48th order harmonic operations can be obtained. The signal to noise ratio (SNR) of the

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corresponding radio frequency (RF) spectrum is 66.79 dB, 61.37 dB, 54.82 dB and 49.66 dB. The stable mode-locked pulse modulated by digital signal and is transmitted in a simulated atmospheric turbulence device. The eye patterns can be obtained at the condition of ΔT=70 ℃, 140 ℃, 210 ℃ and back-to-back (BTB). The SNR at ΔT=210 ℃ decreased 9.14 dB compared with BTB condition.

Keywords: fiber laser; actively mode-locked; free-space optical communication; atmospheric turbulence

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1 引 言

近年来，锁模光纤激光器由于其具有线宽窄、波长可调谐、温度特性好等特点而被广泛研究[1-4]。由于2 μm波段覆盖几个强OH$^-$吸收峰，并且处于大气窗口，因此2 μm光纤激光器可被应用于激光医疗、激光雷达、空间激光通信等领域[5-6]。常用的2 μm波段增益光纤有掺铥光纤和掺钬光纤，掺铥光纤的增益谱范围为1700 nm~2000 nm，掺钬光纤的增益谱范围为2000 nm~2200 nm。根据米氏散射条件，光在大气中传输的散射强度与波长的平方成反比，随着激光波长的红移，受到散射的影响减小。此外，波长大于2 μm的激光避开了CO_2，CH_4等几种常见气体分子吸收峰[7]，因此掺钬锁模光纤激光更适用于空间激光传输系统。

产生GHz量级的锁模脉冲主要有主动锁模和被动锁模两种方式[8-9]，相比于被动锁模，主动锁模可以产生重复频率可调的高重频、高稳定性的脉冲序列，更适用于作为激光通信载波光源。主动锁模产生的原理是通过在谐振腔内加入电光晶体调制器引入周期强度调制，当强度调制的频率是谐振腔基频的整数倍时，可以产生重复频率与调制频率相同的锁模脉冲。这种方法的缺点是在实现锁模的同时会在腔内产生超模噪声，常用的抑制超模噪声的方法主要包括：腔内滤波法、复合腔结构法和非线性效应法[10-12]。其中，腔内滤波法结构简单，可以在抑制超模噪声的同时实现窄线宽、波长可调谐锁模激光输出。近年来，研究人员对2 μm波段高重频锁模脉冲的产生做了大量研究。2016年，Sergei等[13]报道了基于非线性偏振旋转效应的掺钬被动锁模光纤激光器，实验获得了中心波长为2.9 μm，脉冲宽度为180 fs，单脉冲能量达7.6 nJ。2017年，Qin等[14]报道了一个主动锁模皮秒脉冲源，重复频率在1 GHz~6 GHz可调，脉冲宽度60 ps，中心波长为1958.5 nm。2018年，Zeng等[15]使用可饱和布拉格反射器实现了重复频率1.25 GHz，脉冲宽度426 fs，中心波长1941 nm。然而，对于波长大于2 μm的研究主要集中于产生高能量窄脉宽的飞秒脉冲。2018年，Maria等[16]使用可饱和吸收体搭建了全光纤被动锁模掺钬光纤激光器，研究了展宽区锁模脉冲的光谱与谐振腔总色散的关系，输出脉冲宽度为190 fs，脉冲能量为2.55 nJ。目前，有关波长超过2 μm的高重频锁模脉冲的报道相对较少，而针对空间激光通信系统的2 μm锁模光源还未见报道。

本文报道了一种可用于空间激光通信的主动锁模掺钬光纤激光器，谐振腔内通过加入非线性偏振旋转效应滤除超模噪声，提高锁模脉冲的稳定性，同时实现波长可调谐。波长可调谐范围为2058.4 nm~2078.6 nm，最高重频可达1.008 GHz，对应的频谱信噪比为49.66 dB。锁模脉冲被速率为1.008 Gb/s的数字信号调制后在三种不同的湍流条件下进行传输，解调后的眼图信噪比分别为9.35 dB，6.83 dB和4.58 dB。

2 实验结构与工作原理

2.07 μm光纤激光在模拟大气湍流条件中传输的实验结构如图1(a)所示，增益介质为一段1.5 m长的掺钬光纤(Nufern SM-HDF-10/130)。泵浦源为一个实验室自制的掺铥光纤激光器(thulium-doped fiber laser, TDFL)和一个实验室自制的掺铥光纤放大器(thulium-doped fiber amplifier, TDFA)。调制器为带宽10 GHz的商用2 μm波段马赫-曾德尔强度调制器(IXblue MX2000-LN-10)，微波信号源(Hittite HMC-T2220)可以产生频率范围10 MHz~20 GHz的正弦信号，最大输出功率为30 dBm。谐振腔内由两个偏振控制器(polarization controller，PC)和一个偏振相关隔离器(polarization dependent isolator，PD-ISO)组成非线性偏振旋转结构，在实现波长可调谐、保证谐振腔内激光单项传输同时进行光谱滤波，抑制超模噪声[17]。1×2光耦合器(optical coupler，OC)的80%端提供腔内反馈，20%端输出后经过第二个马赫-曾德尔强度调制器对输出的锁模脉冲加载数字信号，经过调制的脉冲信号由掺钬光纤放大器(advalue photonics, AP-AMP1)

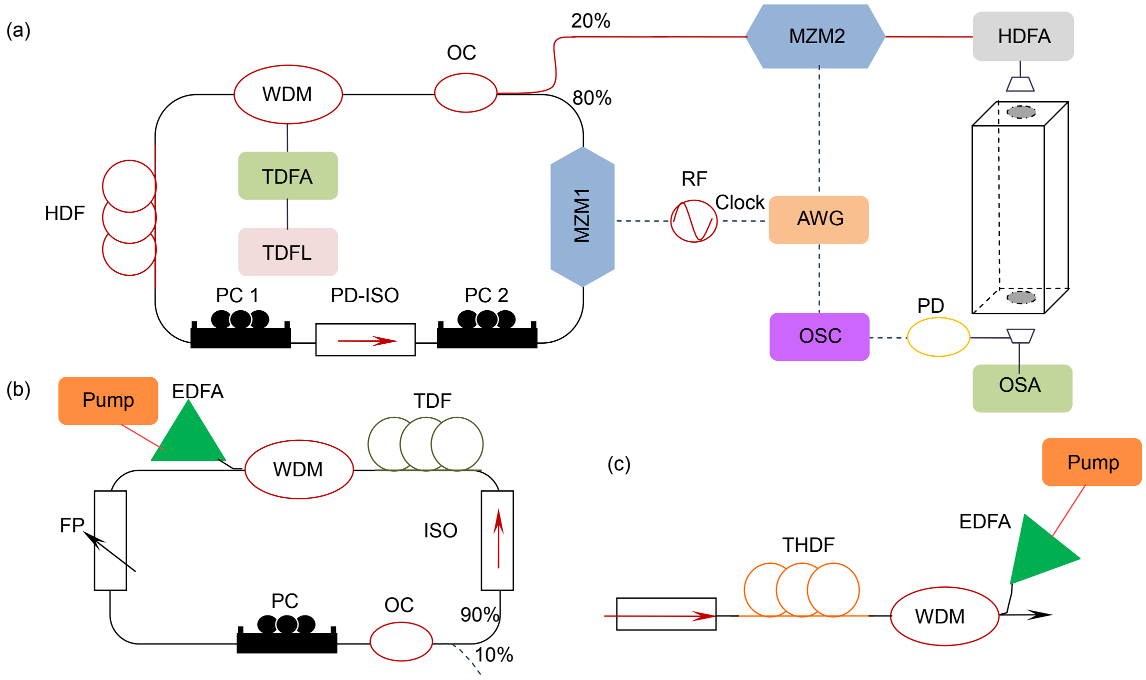

图 1　实验结构。(a) 2.07 μm 主动锁模光纤激光器及室内湍流模拟传输实验结构图；(b) 掺铥光纤激光器泵浦结构图；(c) 掺铥光纤放大器结构图

Fig. 1　Experimental structure. (a) 2.07 μm actively mode-locked fiber laser and transmission system; (b) Thulium-doped fiber laser pump; (c) Thulium-doped fiber amplifier

放大后在模拟大气湍流装置中传输，模拟大气湍流池的两端设置两个光纤准直器进行光路准直。接收端脉冲信号由 2 μm 波段光电探测器探测，带宽为 12 GHz，脉冲时域波形图可以从带宽 2.5 GHz 的示波器(Agilent, DSO 9254A)观测，光谱由光谱分析仪(YOKOGAWA, YQ6375)观测，光谱观测范围为 1200 nm~2400 nm，最小分辨率为 0.05 nm，频谱信号由频谱分析仪(Agilent, N1996A)同步观测，频率范围为 100 kHz~3 GHz。图 1(b)为实验室自制的掺铥光纤激光器结构图，泵浦是中心波长为 1565 nm 的窄线宽代替激光器，经由铒镱共掺光纤放大器(erbium ytterbium co-doped fiber amplifier，EYDFA)放大到 1 W 后泵浦一段 2.5 m 长的掺铥光纤，腔内采用可调谐光滤波器(agilrron FOTF)控制谐振腔输出激光波长，输出激光中心波长为 1900 nm，输出功率为 10 mW。图 1(c)为自制的掺铥光纤放大器结构图，掺铒光纤放大器(connet MFAS)最高输出功率为 5 W，增益光纤采用一段长度为 4 m 的铥钬共掺光纤(INO TH550)，掺铥光纤放大器的可将 1900 nm 的激光功率放大至 1.2 W。

3　结果与讨论

主动锁模通过调制器在腔内引入周期强度调制实现，当调制频率为腔基频的整数倍时可获得稳定的锁模脉冲输出。实验中，谐振腔总长度为 9.52 m，对应基频为 21 MHz。掺铥光纤激光器经放大后功率固定在 1.2 W，获得掺钬主动锁模光纤激光器的光谱如图 2(a)所示，中心波长为 2066.4 nm，3 dB 线宽为 0.09 nm，边模抑制比为 42.05 dB。由于谐振腔内引入非线性偏振旋转效应限制主动锁模激光线宽，在锁模过程中产生的高阶谐波可以被有效抑制，锁模脉冲的稳定性得到提高。另一方面，非线性偏振旋转效应还可以实现波长可调谐，实验获得波长可调谐范围为 2058.4 nm~2078.6 nm，边模抑制比大于 40 dB。

将调制器的偏置电压设置在 $V_{\pi}/2$ 处(V_{π}是调制器的半波电压)，正弦信号源的频率调至 21.013 MHz，可以获得基频模式下的锁模脉冲激光，如图 3(a)所示。脉冲间隔为 47.6 ns，脉冲宽度为 3.74 ns，平均输出功率为 13.3 dBm，锁模脉冲可以稳定运行几个小时，峰峰值抖动较小。增加正弦调制信号频率至 210.118 MHz，504.212 MHz 和 1.008 GHz，分别获得了 10 阶，24 阶和 48 阶谐波锁模脉冲波形，如图 3(b)~3(d)所示。插图反映了小范围时域波形图，可以观测到脉冲间隔分别下降到 4.76 ns，1.98 ns 和 992.06 ps。随着脉冲重复频率的增加，谐振腔内产生更多的超模噪声导致脉

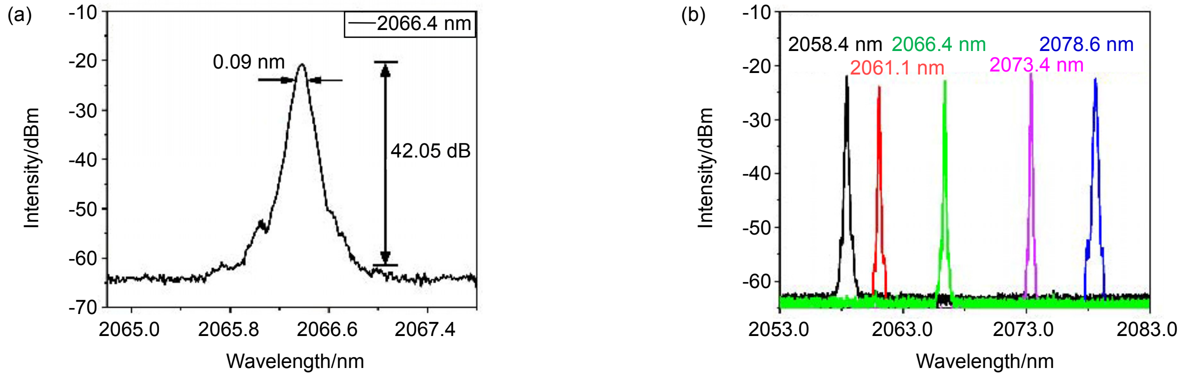

图 2 掺钬主动锁模激光光谱。

(a) 单波长激光输出特性，边模抑制比大于 42 dB；(b) 可调谐激光光谱，2058 nm~2078 nm

Fig. 2 Optical spectra of actively mode-locked holmium-doped fiber laser. (a) Characteristics of single wavelength laser with side-mode suppression ratio greater than 42 dB; (b) Spectra of wavelength tunable laser with tuning range from 2058 nm to 2078 nm

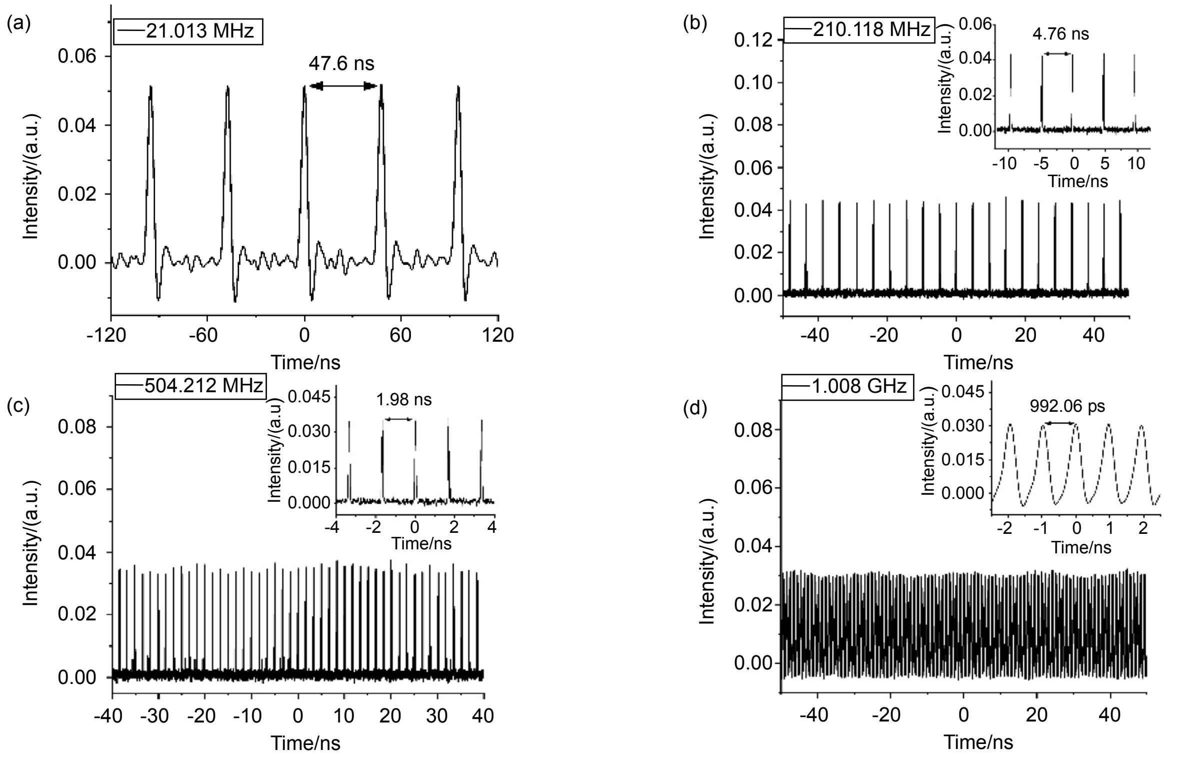

图 3 掺钬锁模激光脉冲序列。

(a) 重复频率 21.013 MHz；(b) 重复频率 210.118 MHz；(c) 重复频率 504.212 MHz；(d) 重复频率 1.008 GHz

Fig. 3 Holmium-doped actively mode-locked pulse sequence.

(a) 21.013 MHz repetition rate; (b) 210.118 MHz repetition rate; (c) 504.212 MHz repetition rate; (d) 1.008 GHz repetition rate

冲的噪底增加，脉冲强度抖动增强，稳定性下降。

为了衡量主动锁模脉冲稳定性与脉冲重复频率的关系，分别测量了 21.013 MHz，210.118 MHz，504.212 MHz 和 1.008 GHz 四种重复频率下的频谱，如图 4(a)~4(d)所示。频谱分辨率为 100 Hz，频域扫描范围分别为 2 MHz，4 MHz，8 MHz 和 16 MHz。基频状态下，锁模脉冲的频谱信噪比可达 66.79 dB，三种谐波对应的频谱信噪比分别为 61.37 dB，54.82 dB 和 49.66 dB。四种锁模状态在频谱扫描范围内无其他边模，说明腔内超模噪声被有效抑制，且锁模脉冲工作在一个稳定的状态。

实验获得的高重频掺钬锁模激光具有线宽窄，稳定性高，位于大气传输窗口等优势，可应用于 2 μm 空间激光通信系统。将主动锁模脉冲调制信号的一半作

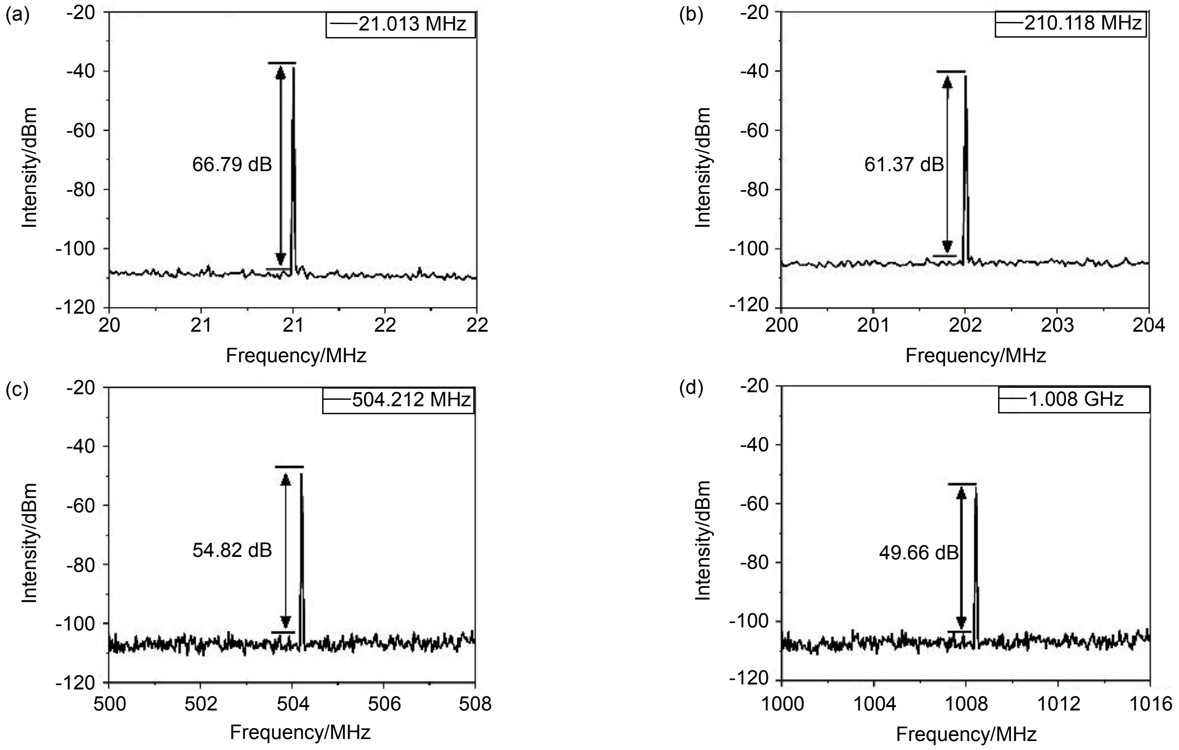

图 4 掺钬主动锁模激光频谱。(a) 重复频率 21.013 MHz; (b) 重复频率 210.118 MHz; (c) 重复频率 504.212 MHz; (d) 重复频率 1.008 GHz

Fig. 4 RF spectra of actively mode-locked holmium-doped fiber laser. (a) 21.013 MHz repetition rate; (b) 210.118 MHz repetition rate; (c) 504.212 MHz repetition rate; (d) 1.008 GHz repetition rate

为外部时钟参考发送至任意波形发生器，任意波形发生器根据时钟同步产生一组相同速率的二进制伪随机码(pseudo-random binary sequence)，经过微波信号放大器放大后驱动第二个马赫-曾德尔调制器对锁模脉冲进行强度调制，脉冲信号的眼图由带宽为 10 GHz 的光眼图仪(Agilent, 86100C)测量获得。由图 5(a)中可以得出背对背传输条件下的光信噪比为 13.72 dB，表明系统噪声容限高，调制深度深。调制后的光脉冲信

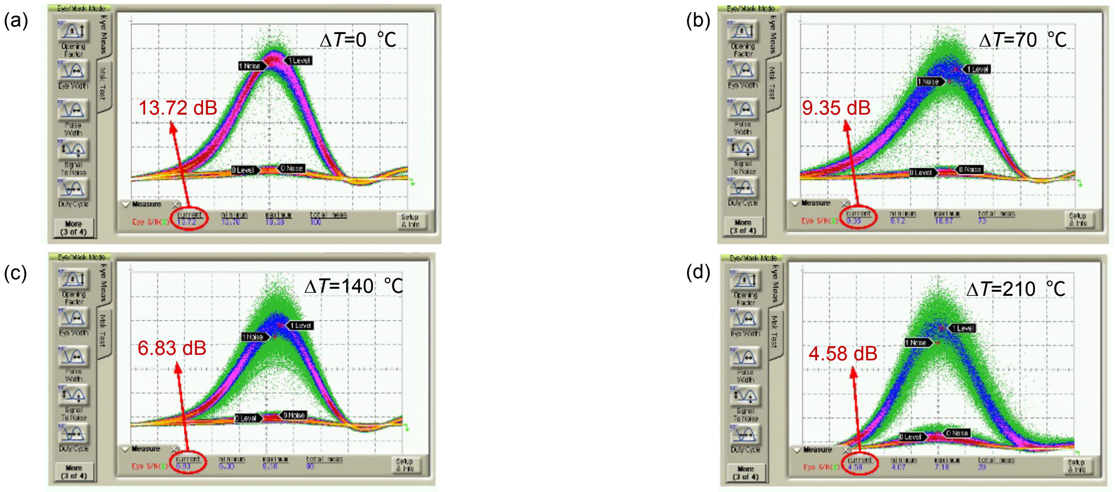

图 5 锁模脉冲在湍流条件下传输眼图。(a) 背对背，光信噪比 13.72 dB; (b) ΔT=70 ℃，光信噪比 9.35 dB; (c) ΔT=140 ℃，光信噪比 6.83 dB; (d) ΔT=210 ℃，光信噪比 4.58 dB

Fig. 5 Eye patterns of mode-locked pulses in different turbulent conditions. (a) BTB, OSNR=13.72 dB; (b) ΔT=70 ℃, OSNR=9.35 dB; (c) ΔT=140 ℃, OSNR=6.83 dB; (d) ΔT=210 ℃, OSNR=4.58 dB

号分别在三种湍流强度条件下传输，接收端通过任意波形发生器发送一组时钟信号进行同步解调，解调后的光眼图如图 5(b)~5(d)所示。随着池体两端的温差升高至 70 ℃，140 ℃和 210 ℃，信道的湍流强度逐渐上升，导致接收光眼图逐渐恶化，眼高变小，噪声容限降低，对应的光信噪比减小至 9.35 dB，6.83 dB 和 4.58 dB。

4 总 结

本文研究了一种主动锁模掺钬光纤激光器并在室内弱湍流条件下进行了传输特性分析。通过在谐振腔内引入非线性偏振旋转效应来实现稳定的高重频、窄线宽锁模脉冲输出，同时实现了 2058.4 nm~2078.6 nm 波长可调谐激光输出。分析了 21.013 MHz，210.118 MHz，504.212 MHz 和 1.008 GHz 四种重复频率下的锁模脉冲时域及频域特性，频谱信噪比为 66.79 dB，61.37 dB，54.82 dB 和 49.66 dB，由于腔内滤波效应滤除了超模噪声，增加了锁模脉冲稳定性。实验获得的掺钬锁模激光经过调制后在三种不同湍流条件下进行传输对比，当池体温差分别增加至 70 ℃，140 ℃和 210 ℃时，调制光信号的信噪比相应地降低了 4.37 dB，6.89 dB 和 9.14 dB。结果表明，主动锁模掺钬光纤激光器在 2 μm 空间激光通信上有潜在的应用价值。

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Propagation characteristics of 2.07 μm fiber laser in weak turbulence condition

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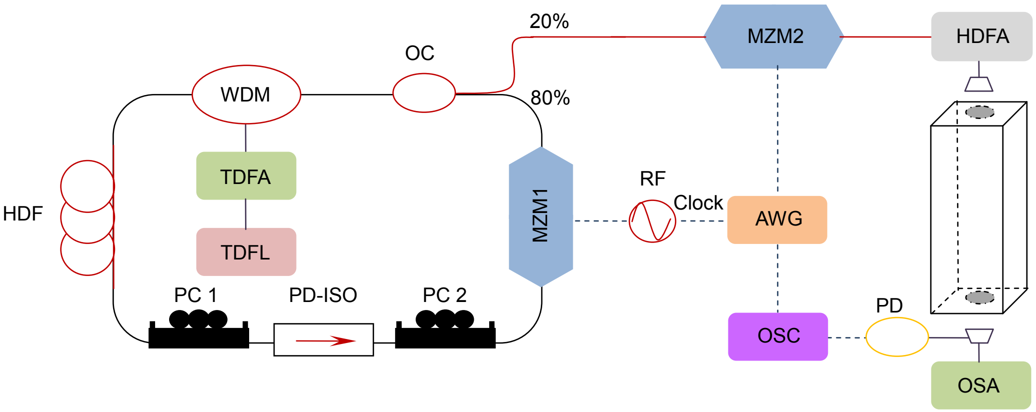

2.07 μm actively mode-locked fiber laser and transmission system

Overview: In recent years, 2 μm band fiber laser has attracted widespread attention with the advent of thulium-doped fiber and holmium-doped fiber because of its wide application in laser medicine, material processing and Lidar. In addition, the 2 μm laser works in atmospheric window, which lays the potential for free-space optical communication. However, the absorption peaks of many common gas molecules gather at 2 μm, such as H_2O and CO_2. The holmium-doped fiber can radiate laser with wavelength greater than 2 μm, which is more suitable as a gain fiber for optical communication laser source than thulium-doped fiber. There are several researches on holmium-doped fiber laser. In recent years, researchers have published a lot of research on the generation of high repetition frequency mode-locked pulse in 2 μm band. In 2017, Qin et al reported an actively mode-locked picosecond (ps) pulsed laser source with the repetition rate of 1 GHz~6 GHz, the pulse width is 60 ps, and the central wavelength is 1958.5 nm. In 2018, Zeng et al realized the repetition rate of 1.25 GHz, the pulse width is 426 fs with a central wavelength of 1941 nm. However, the study of wavelength greater than 2 μm mainly focuses on the generation of femtosecond pulse with high energy and narrow pulse width. In 2016, Sergei et al reported a passively mode-locked holmium-doped fiber laser based on nonlinear polarization rotation, the central wavelength is 2.9 μm, the pulse energy is 7.6 nJ, and a repetition rate of 43.1 MHz. In 2018, Maria et al built a dispersion-managed holmium-doped fiber laser with a graphene saturable absorber, the relationship between the spectrum of the mode-locked pulse and the total dispersion of the resonant cavity was studied, the output pulse width is 190 fs with a repetition rate of 21 MHz. It can be seen that the reports on mode-locked fiber laser with high repetition rate are still insufficient, and the 2 μm fiber laser for free-space optical communication system has not been reported.

In this paper, we demonstrated an actively mode-locked holmium-doped fiber laser, which can be used in free-space optical communication. By adding nonlinear polarization rotation effect in the cavity to filter out super-mode noise, the stability of mode-locked pulse was improved and the wavelength tunable can be realized. The wavelength tuning range is 2058.4 nm to 2078.6 nm, the repetition rate is 1.008 GHz and the corresponding radio frequency (RF) signal-to-noise ratio can reach 49.66 dB. Moreover, the mode-locked pulse sequence was modulated by the digital signal and transmitted under three different turbulent conditions. The optical signal-to-noise ratio of eye diagram after demodulation is 9.35 dB, 6.83 dB and 4.58 dB, respectively.

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