

基于非保偏光纤环腔的启钥式耦合光电振荡器

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摘要 耦合光电振荡器利用有源再生主动锁模技术极大地缩短了光纤环腔长度,有效提升了低相噪光电振荡器的集成度与稳定性。针对传统耦合光电振荡器存在的偏振敏感和超模杂散问题,本团队构建了基于 180 m 非保偏光纤环腔的启钥式耦合光电振荡器,实现了耦合光电振荡器的开机稳定起振和超模杂散抑制,产生的 10 GHz 射频信号相位噪声和杂散抑制比分别优于 -125 dBc/Hz@10 kHz 和 76.3 dB。

关键词 光纤光学; 低相噪振荡器; 启钥式耦合光电振荡器; 偏振不敏感

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低相噪射频信号源在雷达通信、航空航天、测量仪器和科学研究等领域都发挥着重要作用^[1-3]。作为一种新型的信号发生器,光电振荡器利用长距离光纤链路替代传统射频谐振腔作为信号储能元件,能够产生百 MHz 到百 GHz 频率范围的高频谱纯度射频信号,且信号的相位噪声水平与工作频段无关,是高频电子系统理想的信号发生装置^[4-5]。长距离光纤链路是传统光电谐振腔内的高 Q 储能介质,能够得到低相噪微波信号。2008 年,Eliahu 等^[6]利用 16 km 长光纤产生了 10 GHz 超低相噪射频信号(6 kHz 频偏处的相位噪声低至 -163 dBc/Hz)。然而,长距离储能光纤不仅会导致谐振模式间隔降至几十 kHz 量级,进而引入杂散分量,甚至引发模式跳变,还会使光电振荡器出现体积大、控制难和稳定性低等难题。

耦合光电振荡器(COEO)将主动锁模与光电谐振技术结合^[7],利用有源光纤环腔的再生增益特性极大地增强了储能环路的有效品质因子,同时用百米再生锁模环路替代长光纤储能链路,实现了高 Q 射频振荡和高频谱纯度射频信号产生,极大地降低了光电振荡系统的体积、重量和稳定控制的难度。由于耦合光电振荡器中射频选模滤波器品质因子受限,百米光纤环腔再生锁模过程会存在超模杂散问题,从而导致耦合光电振荡模式跳变甚至无法起振。此外,传统的耦合光电振荡器的再生锁模效果对腔内光偏振态极为敏感,百米环腔内的光偏振态容易受到外部环境变化的扰动,从而易使耦合光电振荡器模式发生跳变甚至无法起振。

为了实现耦合光电振荡器开机启钥工作,需要解

决传统耦合光电振荡器存在的偏振敏感和超模杂散难题。本团队基于电吸收调制和半导体光放大构建了 180 m 非保偏有源光纤锁模环腔,解决了耦合光电振荡器存在的上述难题,实现了 10 GHz 启钥式耦合光电振荡器。该耦合光电振荡器最终产生的低相噪信号的相位噪声和杂散抑制比分别优于 -125 dBc/Hz@10 kHz 和 76.3 dB,为耦合光电振荡器的实用化发展提供了重要的技术支撑。

图 1 是基于非保偏光纤环腔的启钥式耦合光电振荡器的结构示意图,该系统主要包括有源非保偏光纤锁模环腔和射频反馈放大回路。为了实现耦合光电振荡环路开机自起振和稳定振荡输出,180 m 非保偏光纤环腔采用电吸收调制器(EAM),同时将半导体光放大器(SOA)作为再生锁模元件和放大增益介质。耦合光电振荡器利用电吸收调制的偏振不敏感特性和半导体光放大的快速增益饱和效应实现抗偏振扰动和超模杂散抑制。

为了实现耦合光电振荡环路开机自起振和稳定振荡输出,本团队首先测试了非保偏有源光纤环腔开环链路的偏振工作特性,测量装置如图 2(a)所示。在非保偏有源光纤环腔开环链路中分别注入连续线偏激光和 10 GHz 射频信号,通过级联高频光电探测器和射频频谱仪(R&S FSWP50)观察记录环腔链路在不同光信号偏振态时(随机连续调节偏振控制器 PC)的调制增益情况,进而评估实验中耦合光电振荡器内光信号偏振态发生扰动时环腔锁模状态的稳定程度。如图 2(b)所示,非保偏有源光纤环腔开环链路的调制增益在 60 min 内的波动小于 2.07 dB,在耦合光电振荡

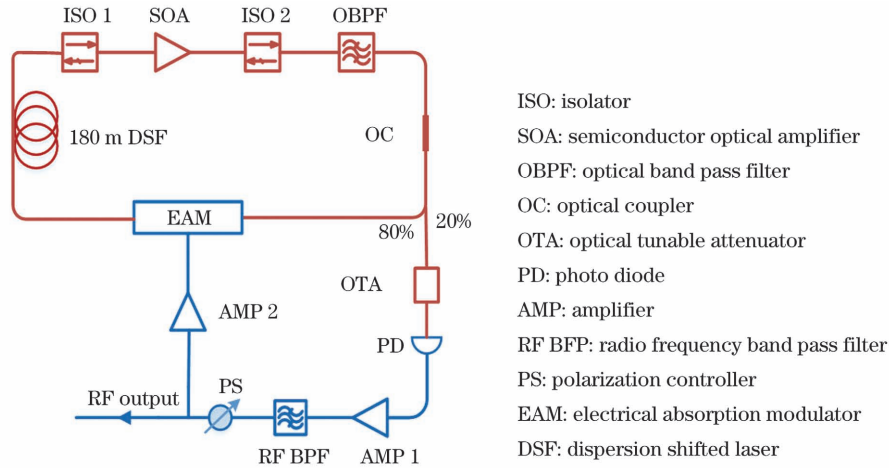


图 1 基于非保偏光纤锁模环腔的启钥式耦合光电振荡器的结构

Fig. 1 Structure of turnkey-coupled optoelectronic oscillator (COEO) based on non-polarization-maintaining fiber cavity

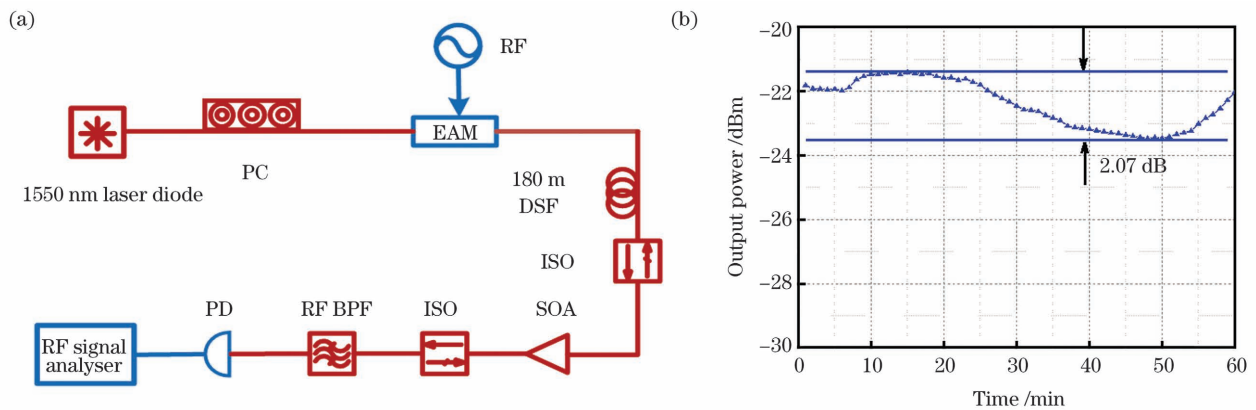


图 2 基于电吸收调制器的非保偏光纤环腔链路抗偏振扰动测试。(a) 测试链路示意图; (b) 调制增益波动

Fig. 2 Diagram of anti-polarization disturbance testing for non-polarization-maintaining fiber cavity based on electrical absorption modulator (EAM). (a) Schematic of measurement link; (b) modulation gain fluctuation

器射频反馈放大环路的锁模增益容忍范围内。

图 3 所示为启钥式耦合光电振荡器与传统耦合光电振荡器的抗偏振扰动特性测试结果,其中传统耦合光电振荡器分别采用铌酸锂强度调制器和掺铒光纤放大器作为再生锁模和放大增益元件。随机连续调节两

个光纤环腔内光信号的偏振态,然后通过射频频谱仪读取并记录两种耦合光电振荡器输出信号射频频谱在 350 s 内的变化情况。图 3(a)、(b)分别为启钥式耦合光电振荡器和传统耦合光电振荡器的输出信号频谱特征,可见:启钥式耦合光电振荡器的起振频率与起振模

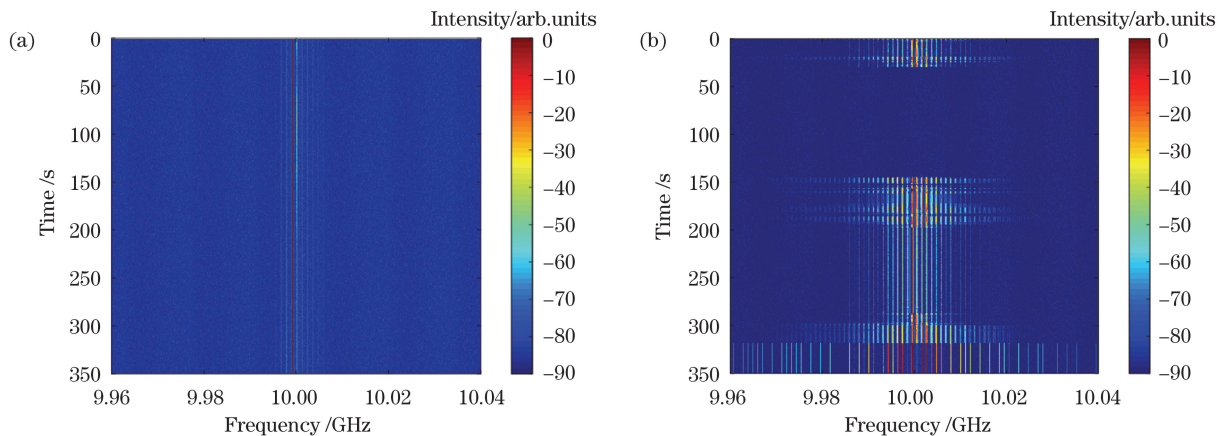


图 3 启钥式耦合光电振荡器与传统耦合光电振荡器的抗偏振扰动特性对比。(a) 启钥式耦合光电振荡器; (b) 传统耦合光电振荡器

Fig. 3 Anti-polarization disturbance performance comparison of turnkey COEO and conventional COEO. (a) Turnkey COEO; (b) conventional COEO

式在 350 s 内没有发生变化,并且保持稳定的单模振荡。相比之下,传统耦合光电振荡器的输出信号频谱变化较大,出现了多模振荡与环腔失振等现象。

图 1 所示的启钥式耦合光电振荡器开机启动产生了 10 GHz 的射频信号,该信号经过 3 dB 功分器后馈入相位噪声分析仪(R&S FSWP50)中,输出信号的射

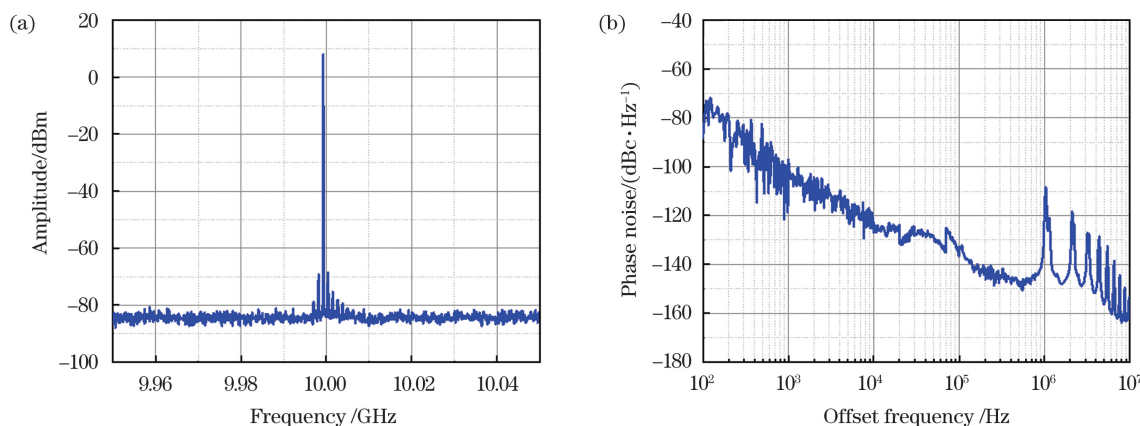


图 4 启钥式耦合光电振荡器输出信号的测量结果。(a)射频频谱;(b)相位噪声

Fig. 4 Measurement results of output signal of turnkey COEO. (a) RF spectrum; (b) phase noise

综上,本团队构建了基于非保偏有源光纤环腔的启钥式耦合光电振荡器,解决了传统耦合光电振荡器无法开机自起振与稳定振荡的问题,该启钥式耦合光电振荡器具有良好的抗偏振扰动和超模杂散抑制能力。基于 180 m 有源光纤锁模环腔的启钥式耦合光电振荡器实现了低相位噪声的 10 GHz 射频信号产生,10 kHz 频偏处的相位噪声低于 -125 dBc/Hz,信号杂散抑制比可达 76.3 dB。本团队后续将进一步优化光纤环腔结构参数,以降低输出射频信号的相位噪声,并将继续开展启钥式耦合光电振荡器的集成化应用研究。

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频频谱如图 4(a)所示,信号功率和杂散抑制比分别为 7.8 dBm 和 76.3 dB。输出信号的相位噪声如图 4(b)所示,信号在 10 kHz 和 10 MHz 频偏处的单边带相位噪声分别低于 -125 dBc/Hz 和 -160 dBc/Hz,并且近载频处的相位噪声还可以通过 Q 值提升(增加腔长)、环腔色散管理和脉冲啁啾补偿等进一步得到改善。

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Turnkey Coupled Optoelectronic Oscillator Based on Non-Polarization-Maintaining Fiber Ring Cavity

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Abstract

Objective Low-noise radio-frequency (RF) signal sources play an essential role in many fields and applications, such as radar, wireless communication, aerospace, measurement instruments, and scientific research. The optoelectronic oscillator uses a long fiber link to replace the traditional RF resonator as the high-Q-energy storage element, but this leads

to issues related to the large volume, control difficulty, and poor stability. The coupled optoelectronic oscillator (COEO) uses active regeneration mode-locking technology to significantly shorten the length of the fiber ring cavity, which effectively improves its integration and stability. It is necessary to solve the issues of polarization sensitivity and supermode spurious for turnkey-coupled optoelectronic oscillators to realize self-start-up and stable single-mode oscillation.

Methods The proposed turnkey-coupled optoelectronic oscillator mainly comprises an active non-polarization-maintaining fiber mode-locked ring cavity and an RF feedback amplification loop. In the 180 m non-polarization-maintaining fiber ring cavity, an electric absorption modulator (EAM) and a semiconductor optical amplifier (SOA) are used as the regenerative mode-locked element and amplification gain medium, respectively, to achieve self-starting capability and stable oscillation. In addition, the polarization insensitivity of the electric absorption modulation and the rapid gain saturation effect of the semiconductor optical amplification can help realize anti-polarization disturbance and supermode spurious suppression for the turnkey-coupled optoelectronic oscillator.

Results and Discussions A turnkey-coupled photoelectric oscillator is demonstrated. The modulation gain fluctuation for an active fiber ring cavity is lower than 2.07 dB in 60 min, which is within the tolerance range for the mode-locked gain of the RF feedback amplification loop. In addition, the issues of the mode spurious and polarization disturbance are resolved, and the proposed 10 GHz oscillator can maintain stable single-mode oscillation after startup. Finally, the phase noise and spurious rejection ratio of the generated signal can reach -125 dBc/Hz at 10 kHz and 76.3 dB, respectively, which would significantly facilitate the development of coupled optoelectric oscillators.

Conclusions In this study, a turnkey-coupled optoelectronic oscillator based on a 180 m non-polarization-maintaining active fiber ring cavity has been constructed to solve the issues of self-starting and stable oscillation owing to anti-polarization fluctuation and supermode spurious suppression. Finally, a 10 GHz RF signal is successfully generated with phase noise at a 10 kHz frequency offset lower than -125 dBc/Hz and a signal spurious suppression ratio of approximately 76.3 dB.

Key words fiber optics; low phase noise oscillator; turnkey-coupled optoelectronic oscillator; polarization insensitive