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基于电吸收调制激光器的双功能微波光子系统

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摘　要:提出了一种基于电吸收调制激光器的双功能系统,可以同时实现微波信号的产生和其相位噪声的测量。该系统由基于电吸收调制激光器的光电振荡器模块和基于光延时线技术的相位噪声测量模块构成。通过使用单个电吸收调制激光器代替激光源和强度调制器,所提出的双功能系统不仅成本低廉、结构简单,而且性能表现优异;有利于在基于OEO的射频系统,特别是信号产生系统的研制、优化与工作过程中,及时评估信号源的质量并作出相应的参数调整以优化其性能,为光电振荡器的相位噪声测试提供了简单的解决方案。实验结果表明,由光电振荡器生成的9.952 GHz信号的边模抑制比为66 dB,相位噪声为−116.53 dBc/Hz@10 kHz。此外,相位噪声测量系统的相位噪声基底达−133.71 dBc/Hz@10 kHz,其测量灵敏度优于商用信号分析仪R&S FSV40。

关键词:相位噪声测量;微波信号产生;微波光子;光电振荡器;电吸收调制激光器
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0　引言

微波信号源是导航、雷达、通信等系统的关键部件[1-2],其性能对现代射频(Radio-frequency, RF)系统有着举足轻重的影响。光电振荡器(Optoelectronic Oscillator, OEO)是一种新型的微波信号源,能够直接产生低相位噪声的高频微波信号[3-4]。因此,OEO被视作一种极具潜力的高性能微波信号产生的方案。相位噪声是评价包括OEO在内的微波信号源性能的重要参数之一。当前,研究人员已提出并实现了一系列的相位噪声测量(Phase Noise Measurement, PNM)方法,包括直接频谱法、鉴相法和鉴频法[5],以准确测量微波信号源的相位噪声。在上述方法中,鉴频法由于无需额外的低相噪微波振荡器作参考源,吸引了研究人员的广泛关注。然而,由于该方法的测量灵敏度与延时有关,受限于电缆的高损耗,其测量灵敏度有限。为此,研究人员提出了一种基于光延时线的PNM方法,通过一卷低损耗的光纤代替电缆来提供长延时,从而提高了测量灵敏度[6]。近年来,为提高基于光延时线PNM系统的整体性能,研究人员开展了大量的工作[7-10]。例如,通过采用微波光子移相器和微波光子混频器代替传统光延时线PNM系统中的电移相器和电混频器,以扩展工作带宽[7-8]。在文献[9, 10]中,利用数字相位解调技术来免除相位噪声测量中的校准过程,以提高测量速度。然而,现有基于光延时线的PNM方案的一个普遍问题在于,过多分立的电子和光学元件的使用使得系统体积庞大,且耦合损耗高。此外,目前光延时线PNM系统的功能性较为单一,仅具备相噪测量的功能,具有双功能或多功能的方案鲜有报道[11]。但是,在基于OEO的射频系统,特别是信号产生系统[12]的研制、优化与工作过程中,为及时评估信号源的质量并作出相应的参数调整以优化其性能,研发一种成本低廉、简单紧凑的相位噪声测量方案十分必要。

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本文提出了一个基于光子学的双功能系统，利用电吸收调制激光器(Electro-absorption Modulated Laser, EML)实现了微波信号的产生和相位噪声的测量。在该系统中，基于EML搭建了一个结构紧凑的OEO，同时通过基于EML的光延时线方法实现了相位噪声测量。通过单个EML代替激光器和强度调制器[13-14]，本方案所提出的基于光子学的双功能系统不仅具有成本低廉、结构简单等优势，且性能表现优异。实验中，基于EML的OEO模块生成的9.952 GHz微波信号的边模抑制比(Side Mode Suppression Ratio, SMSR)为66 dB，相位噪声为−116.53 dBc/Hz@10 kHz，其相噪表现优于商用信号源Anritsu MG3692B。此外，PNM模块的测量灵敏度达−133.71 dBc/Hz@10 kHz，优于商用信号分析仪R&S FSV40。实验结果表明，本系统能在产生高质量微波信号的同时，灵活地为任意内部或外部微波信号源提供高灵敏度相位噪声测量的解决方案。

1　实验装置与原理

基于EML的微波信号产生和相位噪声测量的双功能系统的原理示意如图1，其关键元件是一个10 GHz的EML，它由一个激光二极管和一个电吸收调制器单片集成[14-15]。系统中，OEO模块与PNM模块共用一个EML，用作光载波的产生与强度调制，随后经一个80∶20的光耦合器1，将EML的输出信号分成两部分，分别用于OEO模块和PNM模块。

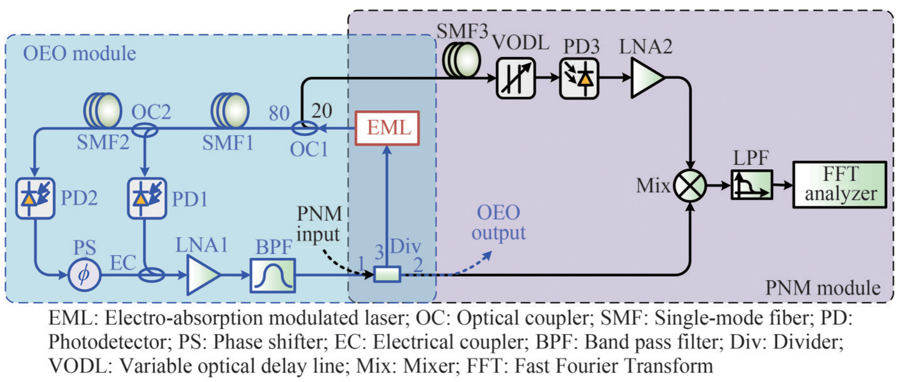


图1　基于EML的微波信号产生和相位噪声测量双功能系统的原理示意

Fig. 1　Schematic of the EML-based dual-functional system for microwave signal generation and phase noise measurement

1.1　光电振荡器模块

在OEO模块中，EML产生的调制光信号首先通过一卷单模光纤1，随后经一个50∶50的光耦合器2分为两束。其中一半光信号直接输入光电探测器1，而另一半则经另一卷单模光纤2后输入光电探测器2。经光电探测器1和光电探测器2作光电转化后，输出的两路电信号经一个50∶50的电耦合器耦合为一路，依次通过一个低噪声放大器1和一个带通滤波器后反馈回EML中，以形成一个闭合的振荡环路。其中，使用了双环结构以抑制振荡腔内的边模[16]，且在长环路中插入了一个移相器来调节该环路的等效长度。最终，所生成的微波信号经电功分器输出，以便输入商用信号分析仪或PNM模块测量其振荡频率与相位噪声。

1.2　相位噪声测量模块

PNM模块中，来自OEO模块或其他模块的待测微波信号经功分器分为两个支路。在下支路中，待测微波信号直接输入混频器的一端。在上支路中，来自EML的调制光信号通过单模光纤3以获得长延时，随后经过可调光延时线，从而引入上下两支路间可调谐的相位差。随后，光信号输入光电探测器3转换为电信号，经低噪声放大器2作功率补偿后，再输入混频器与下支路信号相混频。最后，经低通滤波器提取混频器输出的基带信号，输入快速傅里叶变换(Fast Fourier Transform, FFT)分析仪中计算待测微波信号的相位噪声[6]。

2　实验结果与分析

根据图1搭建了基于EML的微波信号产生和相位噪声测量双功能系统。实验中，使用的EML为

Fiber-photonics公司生产的商用器件,中心波长为1 551.32 nm,3-dB带宽为10 GHz。光电探测器1和光电探测器2的3-dB带宽为30 GHz,灵敏度为0.85 A/W。光电探测器3的3-dB带宽为18 GHz,灵敏度为0.8 A/W。带通滤波器的3-dB带宽为20 MHz,中心频率为9.95 GHz。低噪声放大器1和低噪声放大器2的工作频率范围为8~18 GHz,增益为45 dB。可调光延时线的调谐范围为0~1 500 ps,调节精度为10 fs。低通滤波器的3-dB截止频率为5 MHz。由Keysight公司生产的N9020A FFT分析仪被用于采集LPF输出的基带信号并作相位噪声计算。OEO的性能主要由带宽为40 GHz的商用信号分析仪R&S FSV40表征,其光谱由分辨率为0.02 nm的光谱分析仪Ando AQ6317B监测。

2.1 光电振荡器模块的性能测试

在OEO模块中,首先对EML的特性进行了研究。如图2,通过调节电吸收调制器的偏置电压,测量其对应的输出光功率:当反向偏置电压从0 V增加到−1.5 V时,EML的输出功率从5.39 dBm下降到−2.01 dBm。

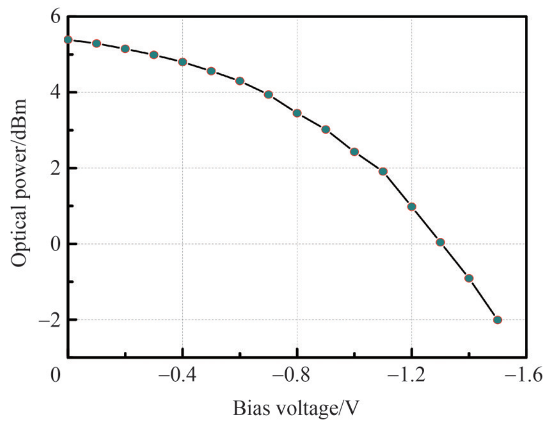


图2 EML输出功率与其偏置电压的关系

Fig. 2 EML output power versus its bias voltage

实验中,选取的单模光纤1和单模光纤2的长度分别为2 km和0.1 km。当EML中电吸收调制器的偏置电压为−0.7 V时,测量了OEO信号的光谱和频谱。图3(a)为EML输出端的光谱,可以观察到几个等间距的光边带,该结果意味着OEO环路中已形成了一个稳定的模式振荡。这一结论可以通过观察信号的频谱作进一步验证。如图3(b),将电功分器的输出端连接信号分析仪,可以观察到一个频率为9.952 GHz的微波信号。需要指出的是,通过在反馈环路引入可调的信号延时或相位,可在滤波器的通带范围内实现一定的频率调节能力。进一步通过采用中心频率可调的电滤波器或微波光子滤波器,可使OEO具备更大范围的频率调节能力[17-20]。此外,由于2 km和2.1 km的双环结构所引起的游标卡尺效应,振荡腔内的边模可以得到有效的抑制。因此,信号的SMSR达到了66 dB。

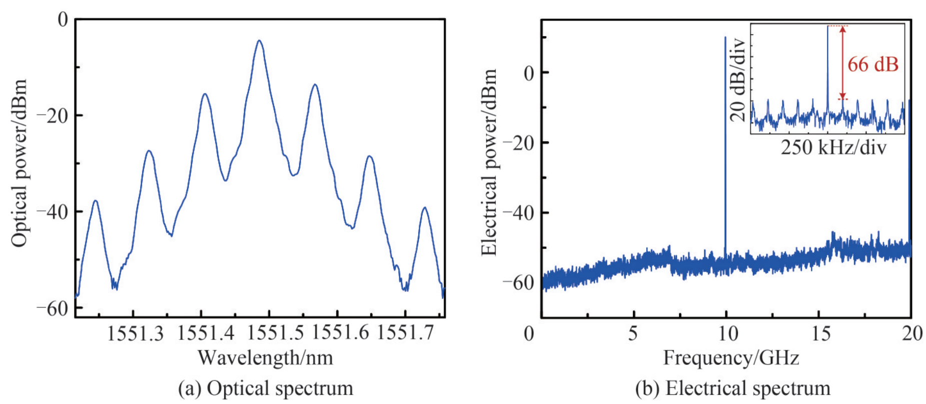


图3 OEO模块的光谱与频谱

Fig. 3 Optical and electrical spectra of the OEO module

2.2 相位噪声测量模块的性能测试

对PNM模块的性能进行了相应测试。为验证基于EML的PNM模块的测量准确性，首先测量了一个10 GHz微波振荡器(BZB10G)的相位噪声。实验中，EML的偏置电压保持在−0.7 V，使用的单模光纤3长度为2 km。图4给出了PNM模块(黑色曲线)和R&S FSV40(红色曲线)的相位噪声测量结果的比较。如图4，基于EML的PNM模块在偏移频率大于1 kHz时，与商用信号分析仪的相位噪声测量结果保持着较好的一致性，证明了所构建的PNM系统的测量结果是可信的。在频偏小于1 kHz时，测量结果存在着轻微的差异，该差异可能是由于光电探测器3的闪烁噪声所引起的[21]。

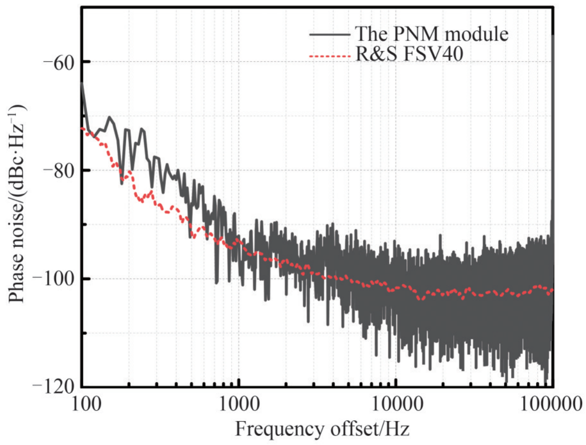


图4 10 GHz微波振荡器的相位噪声

Fig. 4 Measured phase noise of a 10 GHz microwave oscillator

为验证PNM模块的测量灵敏度，根据文献[7]中所述的方法，使用一个具有相同损耗的光衰减器代替长度为2 km的单模光纤3，测量了PNM模块的相位噪声基底。作为比较，图5(a)中绘制了商用信号分析仪的相位噪声基底。在10 GHz载波下，PNM模块在10 kHz频偏处的相位噪声基底为−123.73 dBc/Hz，优于R&S FSV40(约−104.9 dBc/Hz @10 kHz @10 GHz)，该结果证明了PNM模块的高测量灵敏度。如图5(b)，还探究了使用不同长度单模光纤3时PNM模块的相位噪声基底。实验结果表明，随着光纤长度的增加，测量系统的灵敏度得到了提高，但测量的有效频偏范围也随之减小[6]。具体地，当光纤长度为5 km时，PNM模块的相位噪声基底达−133.71 dBc/Hz @10 kHz。

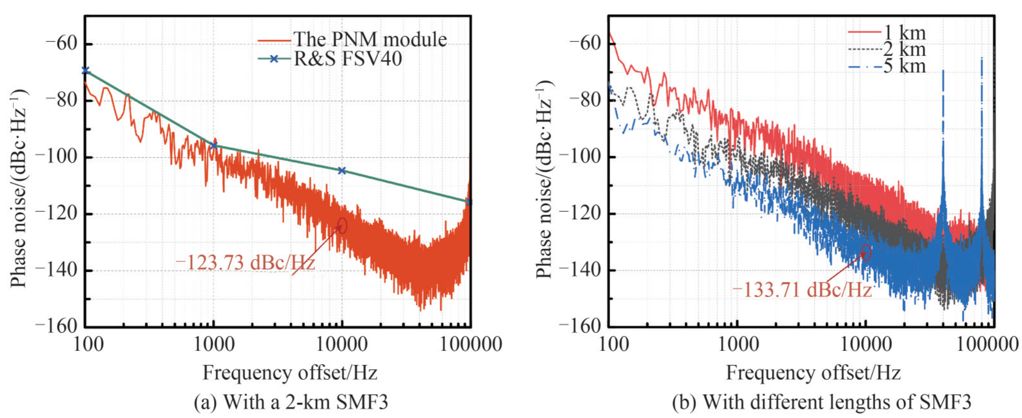


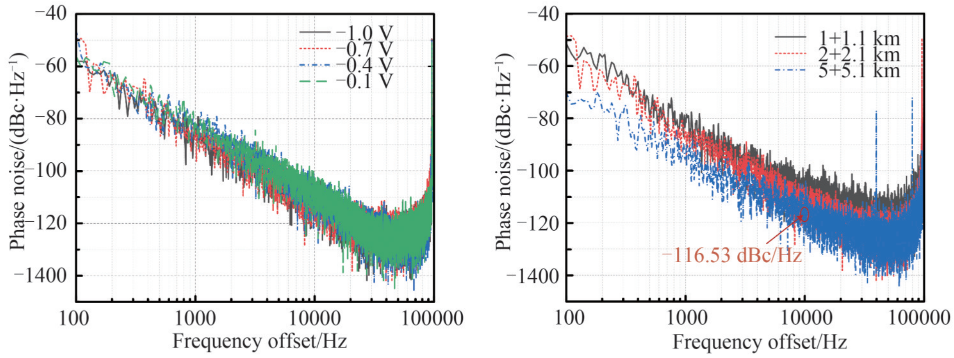
图5 PNM模块的相位噪声基底

Fig. 5 Phase noise floor of the proposed PNM module

2.3 双功能系统的性能测试

使用PNM模块测量了OEO模块产生的9.952 GHz信号的相位噪声。如图6所示，探究了相位噪声与EML偏置电压和光纤长度的变化关系。图6(a)为当单模光纤1的长度固定为2 km时，在不同的EML偏置

电压下测量的OEO的相位噪声。当偏置电压为−0.1 V、−0.4 V、−0.7 V和−1.0 V时,10 kHz频偏处OEO的相位噪声分别为−109.62 dBc/Hz、−110.89 dBc/Hz、−113.82 dBc/Hz和−111.97 dBc/Hz。结果表明,所生成微波信号的相位噪声均低于−109 dBc/Hz @10 kHz,且其波动保持在4.2 dB以内。图6(b)给出了使用三段不同长度的单模光纤1(1 km、2 km和5 km)时,所生成微波信号的相位噪声结果,其中单模光纤2长度固定为0.1 km,EML偏置电压保持在−0.7 V。随着光纤长度的增加,由于OEO的品质因数的提高,所生成信号的相位噪声也随之降低,该实验结果与理论相吻合[3]。当使用1 km、2 km和5 km的单模光纤1时,10 kHz频偏处的相位噪声分别为−107.52 dBc/Hz、−113.82 dBc/Hz和−116.53 dBc/Hz。



(a) With different EML bias voltages (b) With different fiber lengths

图6 由PNM模块测得的OEO模块的相位噪声

Fig. 6 Phase noise of the OEO module measured by the PNM module

如图7所示,比较了使用2 km单模光纤1时,基于EML的OEO与商用信号源(Anritsu MG3692B)产生的同频信号的相位噪声。可以看出,OEO在大于1 kHz频偏处,具备更好的相噪表现。具体而言,OEO生成的微波信号的相位噪声达−113.82 dBc/Hz@10 kHz,较Anritsu MG3692B(−88.3 dBc/Hz@10 kHz)低25.52 dB。然而,由于系统中闪烁噪声的影响[2],OEO模块在低频偏处的相位噪声较高。通过使用低相位噪声的放大器和其它低噪声的器件来减小系统内的闪烁噪声,可以进一步抑制OEO在频偏小于1 kHz处的相位噪声。

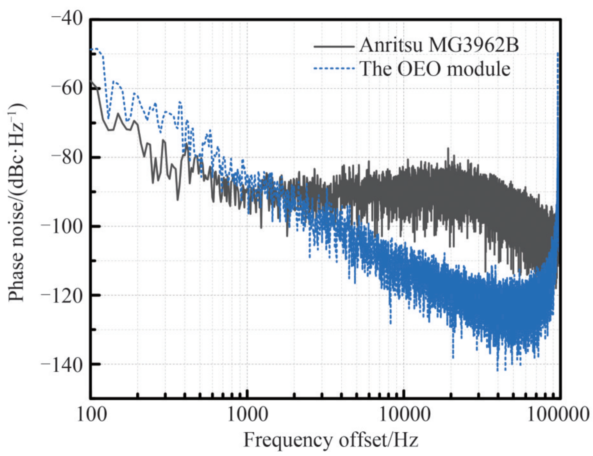


图7 OEO模块与Anritsu MG3962B的相位噪声

Fig. 7 Measured phase noises of the OEO module and Anritsu MG3962B

3 结论

本文提出并实验验证了一个基于光子学的双功能系统,系统可同时实现微波信号的产生和相位噪声的测量。利用单个EML代替激光器和强度调制器,所提出的基于光子学的双功能系统不仅具有成本低廉、结构简单等优势,且性能表现优异。实验中,基于EML的OEO模块所生成的9.952 GHz信号的SMSR为

66 dB，相位噪声为−116.53 dBc/Hz@10 kHz，较Anritsu MG3692B生成同频信号的相位噪声低25 dB以上。此外，PNM模块的相位噪声基底达−133.71 dBc/Hz@10 kHz，其测量灵敏度优于商用信号分析仪R&S FSV40。实验结果表明，该双功能系统能够同时产生高性能的微波信号，并为OEO的相位噪声测试提供了简单的解决方案。该方案将有利于在基于OEO的射频系统，特别是信号产生系统的研制、优化与工作过程中，及时评估信号源的质量并作出相应的参数调整以优化其性能。因此，本方案适用于需产生高质量微波信号，并同时需对系统内部或外部不同微波信号的相位噪声作测量的情境。

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Dual-functional Microwave Photonic System Based on Electro-absorption Modulated Laser

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Abstract: Microwave signal generator is the key component of modern Radio-Frequency (RF) systems, such as navigation, radar, communications, and electronic warfare. Optoelectronic Oscillator (OEO), a new type of microwave oscillator, is able to directly generate a high-frequency microwave signal with low phase noise. Therefore, OEO is considered a promising solution for high-performance microwave signal generation. Phase noise is one of the vital parameters to evaluate the performance of microwave signal sources, including OEO. To date, a number of Phase Noise Measurement (PNM) methods have been designed and carried out to accurately measure the phase noise of microwave signal sources, including direct spectrum method, phase detector method, and frequency discriminator method. Among these methods, the frequency-discriminator-based PNM method is more attractive since it can eliminate the requirement of a low phase noise reference oscillator. However, the measurement sensitivity of this method is related to the time delay, which is limited by the large loss of electrical cables. Fortunately, a photonic delay line PNM method has been proposed with a high measurement sensitivity, where a section of optical fiber is applied to provide a long-time delay with negligible loss. In recent years, a lot of efforts have been devoted to improving the overall performance of the photonic delay line PNM system. For instance, a microwave photonic phase shifter and microwave photonic mixer have been employed to replace the electrical phase shifter and mixer of a traditional photonic delay line PNM system to extend the operation bandwidth. In addition, digital phase demodulation is adopted to eliminate the calibration procedure. Nevertheless, a problem with most previous photonic delay line-based schemes is that too many discrete electrical and optical components are used, which makes them bulky and leads to considerable coupling loss. Furthermore, the functionality of current photonic delay line PNM systems is relatively homogeneous, with only phase noise measurement, and few solutions with dual- or multi-functionality have been reported. However, during the development, optimization and operation of OEO-based RF systems, especially signal generation systems, it is necessary to develop a low-cost, simple and compact phase noise measurement solution to evaluate the quality of the signal source in time and make corresponding parameter adjustments to optimize its performance. In this paper, we propose a photonics-based dual-functional system that can achieve both microwave signal generation and phase noise measurement using an Electro-absorption Modulated Laser (EML). In this system, an EML-based optoelectronic oscillator module and a phase noise measurement module based on a photonic delay line method are implemented simultaneously. By replacing the laser source and intensity modulator with a single EML, the proposed photonics-based dual-functional system achieves a low cost and simple structure, as well as maintaining high performance. In the proof-of-concept experiment, a 9.952-GHz signal generated by the EML-based OEO has a side mode suppression ratio of 66 dB and a phase noise of −116.53 dBc/Hz@10 kHz, which is over 25 dB lower than that of Anritsu-MG3692B. In addition, the PNM module has a phase noise floor reaching −133.71 dBc/Hz@10 kHz, which is lower than that of the commercial signal source analyzer R&S FSV40. The experimental results show that the dual-functional system is capable of simultaneously generating a high-performance microwave signal and providing a high-sensitivity phase noise measurement solution for both internal and external microwave signals. This solution will facilitate the development, optimization and operation of OEO-based RF systems, especially signal generation systems, by evaluating the quality of the signal source in time and making the corresponding parameter adjustments to optimize its performance. Therefore, the proposed scheme is suitable for occasions where a high-performance microwave signal is required, and the phase noise performance of different microwave signals within the system can be monitored at the same time.

Key words: Phase noise measurement; Microwave generation; Microwave photonics; Optoelectronic oscillator; Electro-absorption modulated laser

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