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Experimental optimization of phase noise performance of optoelectronic oscillator based on directly modulated laser

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The experimental optimization of a 10 GHz optoelectronic oscillator (OEO) based on a 1.55 μm directly modulated distributed feedback (DFB) laser is demonstrated in this paper. The phase noise of the directly modulated laser (DML) based OEO is significantly reduced by proper selection of the laser's bias current and by using a dispersion shifted fiber as a delay line. The phase noise performance of the DML OEO achieved after optimization is close to that of a conventional OEO constructed using a commercial DFB laser and a $LiNbO_3$ Mach-Zehnder modulator. The DML based OEO is most promising for future realization of a miniature OEO architecture with the components integrated on a semiconductor substrate.

optoelectronic oscillator, directly modulated semiconductor laser, $LiNbO_3$ Mach-Zehnder modulator

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Because of their outstanding ability to generate high frequency microwave signals with extremely low phase noise, optoelectronic oscillators (OEOs) [1] have attracted a great deal of interest for a wide range of photonic and RF systems applications [2,3]. For applications such as radar, electronic warfare (EW), signal intelligence (SIGINT) and high speed signal processing, a miniaturized OEO is highly desirable [4]. Replacement of the bulky fiber delay line with a high *Q* microresonator [5,6] is a major step forward in the efforts to realize a highly integrated OEO. Further miniaturization could be achieved by integrating the electro-optic modulator along with the other components, such as the electro-absorption modulated laser (EML) [7] or the optical whispering gallery mode resonator/modulator [8], but the technical requirements are relatively rigorous and costly.

A directly modulated semiconductor laser (DML) could act as both the laser source and the modulator and is easy to integrate with the other components on a semiconductor substrate, allowing a more compact OEO architecture and further cost reduction. Several research groups have demonstrated OEOs based on either distributed feedback (DFB) lasers [9] or vertical-cavity surface-emitting lasers (VCSELs) [10]. However, their phase noise performance is generally poor (only −80 dBc/Hz @ 10 kHz offset, with 10 GHz center frequency [10]), so that these OEOs are restricted to a few special applications.

The poor phase noise performance mainly comes from the DML's high intrinsic noise under large signal modulation, and from the interplay between the DML and other components in the OEO [11,12]. Recently, Ahmed [13] demonstrated that the DML's intrinsic noise is strongly influenced by the modulation parameters, i.e. bias, modulation current and modulation frequency. Proper selection of the modulation parameters may therefore play a key role in mitigating the impact of these excess noise sources.

In this paper, we have demonstrated the experimental optimization of the phase noise performance of a DML based OEO. It is shown that biasing of the DML at a relatively low current could reduce the OEO phase noise. This performance can be further improved by using dispersion-shifted fibers (DSF) as delay lines. After optimization, the phase noise is close to that of a conventional OEO constructed using a commercial DFB laser and a $LiNbO_3$ Mach-Zehnder modulator (MZM), which is the best result

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reported in the literature for this type of OEO to our knowledge.

1 Phase noise contribution of DML

The phase noise contribution of the DML comes mainly from its relative intensity noise (RIN) and its frequency noise (FN), especially in their baseband frequency regions [11,12]. The physical mechanism can be explained as follows: (1) the baseband RIN produces a fluctuation in the microwave refractive index in the photodetector (PD) and is then up-converted to phase noise [12]; (2) the baseband FN causes a delay time fluctuation via the chromatic dispersion of the fiber, and thus is also converted to phase noise [11]. According to Ahmed's numerical analysis, the modulation parameters influence the noise level of the DML strongly [13]. In that paper, the lowest noise level was achieved when the modulation frequency was much larger than the relaxation frequency, which indicates that a relatively low bias current is recommended for OEO applications. The modulation efficiency of the DML should also be considered, and thus a compromise must be chosen carefully in the experiment. The nonlinear dynamics of the laser would also significantly enhance the intrinsic noise level, so the modulation current amplitude cannot be too large.

2 Experiment

Figure 1 shows the experimental setup of a standard dual loop OEO structure. The output of the DML is first amplified using an erbium-doped fiber amplifier (EDFA). A 3 nm optical bandpass filter is used to reject the amplified spontaneous emission noise. The optical signal is split into two parallel single mode fiber (SMF) delay lines: one is 8 km long and the other is 3 km long. A tunable optical attenuator is inserted into each branch to balance the loop gain. The output from each path is detected separately and the demodulated electrical signals are combined and amplified (26 dB gain), and then pass through an electrical bandpass filter (Q=500 @ 10 GHz) to feed back into the DML. The phase noise is measured using the PN9000C phase noise measurement system from Europtest Co of France.

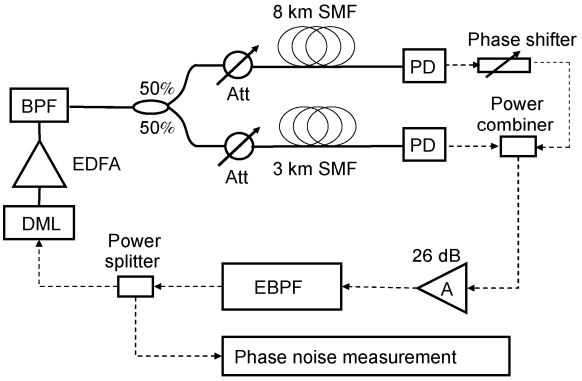

Figure 1 Experimental setup of the DML based dual-loop OEO. BPF: optical bandpass filter; Att: optical attenuator; SMF: single mode fiber; PD: photodetector; EBPF: electrical bandpass filter.

The DML (1550 nm, threshold of 20 mA) used in the experiments was fabricated in our laboratory [16]. First, we investigated its modulation efficiency, which is important because a larger modulation efficiency results in a better signal to noise ratio. We used a vector network analyzer (VNA, Agilent (USA) 8722ET) to measure the gain of the optical microwave link using either the DML or a cascaded 1.55 μm CW DFB laser source (JDSU from USA) and a 40 GHz $LiNbO_3$ MZM (Covega Co. from USA), as shown in Figure 2(a). The electrical driver (SHF 806E) has a gain of 26 dB. The bias current of the DML was tuned from 30 to 90 mA with a step size of 10 mA. The modulation frequency and the input microwave power were fixed at 10 GHz and −15 dBm, respectively, which was also the case for our proposed OEO system. An optical attenuator was inserted to keep the optical power constant (0.8 mW) at the input port of the PD.

The DML reaches its maximum modulation efficiency at 60 mA bias, but drops rapidly above 70 mA because of its limited dynamic range. The modulation efficiency is better than that of the MZM (red line in Figure 2(b)) in the bias regime from 30 to 70 mA, indicating its suitability for the

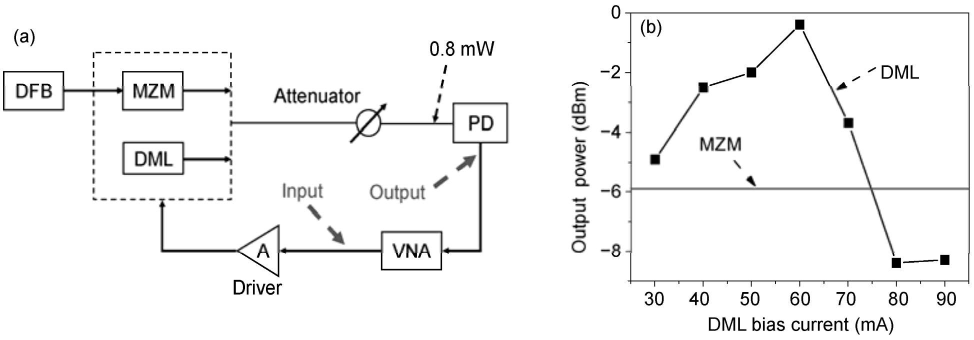

Figure 2 Modulation efficiency comparison between the DML and the $LiNbO_3$ MZM: (a) shows the experimental setup, while (b) shows the output microwave power versus bias current of the DML. VNA: vector network analyzer.

OEO application.

To optimize the OEO's phase noise performance, the bias currents of the DML were chosen to be 40, 60 and 90 mA, with relaxation frequencies of 6.7, 9 and 11 GHz, respectively. The oscillating microwave power is finely adjusted until the best phase noise performance is obtained. As a result, an oscillation power of around 10 dBm is the optimum level for 40 mA bias. Above 10 dBm, the DML exhibits period doubling and the spurs in the phase noise spectrum become intolerable. For 60 and 90 mA bias, the super mode noises increase with increasing oscillating power and we choose a level of 12 dBm for optimal operation. Figure 3(a) shows the optimized single sideband phase noises. It can be seen that the phase noise values obtained at 60 and 90 mA bias are both about 10 dB higher than that at a 40 mA bias. It is reasonable to conclude that this noise discrepancy mainly comes from the variation of the DML's intrinsic noise level at the different bias currents, because the noise contributions from the other parts of the OEO, such as the electrical amplifier, remain the same. This result agrees with the theoretical prediction of Ahmed [13]: the intrinsic noise level (both RIN and FN) is lower when the modulation frequency is much larger than the relaxation frequency of the DML, compared to the case where the modulation frequency is close to the relaxation frequency. Note that the modulation efficiency at 40 mA bias is only 2 dB lower than that at 60 mA bias (Figure 2(b)), and thus the modulation efficiency induced phase noise degradation can be ignored. As a result, we conclude that the DML based OEO achieves its best phase noise performance at 40 mA bias.

As stated in section 1, the baseband FN contributes to the phase noise through its interplay with the chromatic dispersion of the fiber delay line. We therefore replaced the SMFs (~17 ps nm^{-1} km^{-1}) with DSFs (~2 ps nm^{-1} km^{-1}) of the same length to reduce the effects of FN. The measured phase noises are plotted in Figure 3(b). It is clearly shown that the use of the DSF reduces the phase noise by 10–20 dB for each of the three bias currents. The phase noise at 40 mA bias is still much lower than those at 60 and 90 mA, which can be attributed to the relatively higher residual FN and RIN at 60 and 90 mA.

For comparison, we replaced the DML with a commercial 1.55 μm continuous wave (CW) DFB laser source (JDSU) and a 40 GHz $LiNbO_3$ MZM from Covega Co., while the other parts in the OEO loop remain unchanged. DSFs are also used to mitigate the effects of the baseband FN of the CW laser source. The results are shown in Figure 4. The optimized phase noise of the DML based OEO (40 mA bias and using DSFs) is close to that of the OEO using the CW laser source and the MZM. Although additional noise spurs, which may be byproducts of the precursors of period doubling and require further investigation, do exist, the phase noise performance obtained is much better than those reported in the literature. Considering its low cost and the simplicity of its integration, the DML is highly promising for realization of a miniaturized OEO architecture.

3 Conclusions

In this paper, a DML fabricated in our laboratory is used to construct a standard dual loop OEO. The noise level of the laser dominates the phase noise of this OEO. We optimized the phase noise performance by proper selection of the bias current and the modulation strength. The chromatic dispersion of the fiber delay was also reduced to mitigate the FN induced phase noise. The experimental results indicate that: (1) It is recommended that the operating frequency of the OEO is much larger than the DML's relaxation frequency. This result is meaningful because the bandwidth requirement of the DML for an OEO beyond 10 GHz is relaxed to a certain extent. (2) The oscillating power could not be increased infinitely because the occurrence of nonlinear dynamics could degrade the phase noise performance. (3) A photonic microwave energy storage element (the fibers in our experiment) with zero dispersion must be used because the FN of the DML could strongly degrade the OEO's phase noise performance.

The DML is low cost and is easy to integrate with other

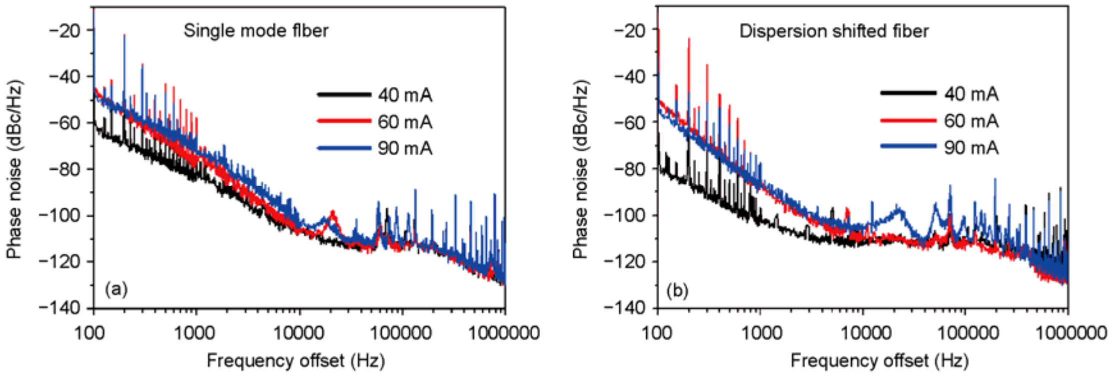

Figure 3 The measured phase noise of the DML based OEO when using (a) SMF, and (b) DSF.

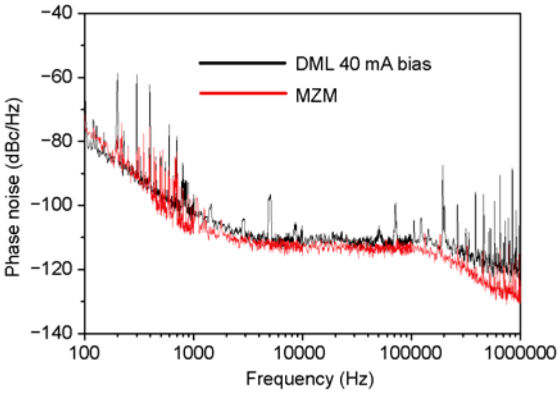

Figure 4 The measured phase noise of the OEO using the DML biased at 40 mA (black line) and a cascaded DFB laser and LiNbO$_3$ MZM. In both cases, DSFs were used.

optoelectronic components. The combination of the DML with a high *Q* microresonator may be a promising way to realize a more compact OEO, or even a single-chip OEO integrated on a semiconductor substrate, allowing for significant cost reduction for applications in future high-speed hand-held devices.

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