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Model for low phase noise microwave photonic link and its application in opto-electronic oscillator

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ABSTRACT

In this paper, the theory model of phase noise for microwave photonic link is derived and verified by experiments first, considering both types of flicker and white noises. In order to decrease the phase noise of link, low-phase noise amplifier and high-linear photodiode is applied in microwave photonic link. Based on this model, the effect of phase noise of microwave photonic link on the OEO is also analyzed and we found the lower-phase noise microwave photonic link results in better-characteristics OEO.

1. Introduction

Opto-electronic oscillator (OEO) is a new kind of microwave source introduced by Yao in 1995 [1,2], and it has been getting more and more attentions due to its super-low phase noise characteristics in microwave and even higher band [3–10]. There are two problems needing to be solved after the appearance of super-low phase noise OEO with long fiber delay: One is the spurs introduced by the small free spectral range (FSR) accompanying long fiber delay, which has been effectively depressed by both schemes of multi-loop OEO [3] and injection locked dual OEO [6]; The other problem is the difficulty for decreasing the OEO's near-dc phase noise determined by colored noise.

Colored noises are the key factors restricting the near-DC phase noise of microwave photonic link (MPL) which is the key part of OEO. Flicker noise, also called $1/f$ noise, is an important part of colored noise and it is the transition band between white noise and other colored noise [11], so decreasing flicker noise in MPL is an effective method decreasing the near-DC phase noise of OEO.

In OEO systems, in order to solve the large-loss problem of the electric delay line, standard telecommunication fiber SMF-28 was used as the delay line due to only 0.2 dB/km loss at 1.55 μm [12–14]. For one thing, the modulated optic signal should be converted back to electric signal and the photodetector (PD) is needed [15]. For the other thing, microwave amplifier could also be used to compensate the optical transmission loss, and amplifier's phase noise also has an impact on the phase noise of OEO. In order to overcome above problems, high-linear PD and the low-phase noise microwave amplifier are utilized in our system, resulting in low phase noise MPL. In following section, we first derive the theoretical model for MPL's phase noise. Then, the effect of the phase noise of MPL on the OEO is analyzed. At last, the high-linear PD and low-phase noise amplifier are applied in MPL and their effects on the phase noise of MPL are analyzed based on experiments.

2. Theory model of phase noise for MPL

MPL consists of kinds of devices, whose noise would be coupled into carrier, and that is the so-called device's phase noise [16,17]. The noise of device is mainly consists of white noise and 1/f noise. The white phase noise results from white noise and is inversely proportional to the input power, which can be expressed by

$$b_0 = \frac{FkT_0}{P_0} \qquad (1)$$

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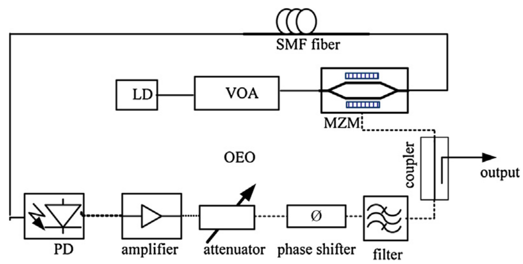

Fig. 1. Schematic diagram of a typical single-loop OEO.

where F is the noise figure, k is the Boltzmann constant, T_0 is the temperature and P_0 is the power of input signal. The link white phase noise is derived as

$$b_{0,t} = \left(F_1 + \frac{F_2 - 1}{A_1^2} + \frac{F_3 - 1}{A_2^2 A_1^2} + \cdots\right)\frac{kT_0}{P_0} \tag{2}$$

$1/f$ noise is another type of noise, which results in $1/f$ phase noise of device. Generally speaking, $1/f$ noise only affects the low frequency signal, but if carrier passes through the nonlinear device, the $1/f$ noise could modulate the carrier and up-converse to higher frequency. Considering white noise and $1/f$ noise, the phase noise of device can be written as

$$S_\varphi(f) = b_0 + b_{-1}\frac{1}{f} \tag{3}$$

where b_0 is power spectrum density of white phase noise and b_{-1} is the $1/f$ phase noise constant. As for cascaded microwave link, since the total $1/f$ phase noise is independent of carrier's power, the whole link's $1/f$ phase noise can be expressed by

$$b_{-1,t} = \sum_{i=1}^{n} b_{-1,i} \tag{4}$$

Based on Eqs. (1)–(4), we can get the cascaded link's phase noise as

$$S_{\varphi,t}(f) = \left(F_1 + \frac{F_2 - 1}{A_1^2} + \frac{F_3 - 1}{A_2^2 A_1^2} + \cdots\right)\frac{kT_0}{P_0} + \sum_{i=1}^{n} b_{-1,i}\frac{1}{f} \tag{5}$$

Summarizing above analysis: Device's phase noise consists of white and $1/f$ phase noise; White phase noise is inversely proportional to carrier's power but $1/f$ phase noise is not influenced by input power; Link's phase noise is the total of every device's contribution.

3. Low phase noise MPL applied in OEO

The configuration of single-loop OEO is shown in Fig. 1. The setup consists of a laser diode (LD), a variable optical attenuator (VOA), a Lithium Niobate Mach–Zehnder intensity modulator (MZM), a Single-mode optical fiber (SMF), a Pin-photodiode (PD), a microwave amplifier, a tunable microwave attenuator, a narrow band filter and a microwave coupler.

The light wave (black line) from the LD is sent to the MZM, modulated by oscillating signal originating from noise at the microwave input port of the MZM, and then sent to the SMF fiber. After transmission through the optical delay line, the optical signals turn into the electrical signals (dashed line) through the PD, after being amplified and filtered, and then feed back to the electric port of the MZM. Signal, whose loop-gain is greater than one and phase-shift is multiples of 2π, is able to oscillate, and detailed theoretical analysis can be found in references [1,2].

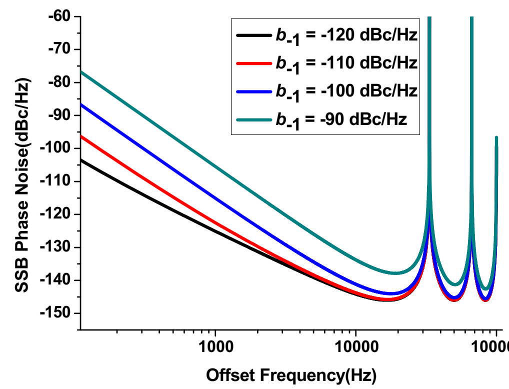

Fig. 2. SSB phase noise of OEO as a function of offset frequency in different values of $b_{-1,t}$.

Based on the quasi-linear theory of OEO, the oscillation power at ω can be derived by [1,2]

$$P(\omega) = \frac{|V_{out}|^2}{2R} = \frac{G_A^2\left\langle V_{in}V_{in}^*\right\rangle/2R}{1 + \left|G(V_0)\right|^2 - 2G(V_0)\cos(\omega\tau - \varphi(\omega))} \tag{6}$$

where V_{in} is the oscillation noise source, G_A is the amplitude gain of amplifier, V_0 is the amplitude of V_{in}, $G(V_0)$ is the closed-loop gain and near 1, τ is the delay time caused by fiber and $\varphi(\omega)$ is the phase shifter of open-loop link. Considering both of white and flicker noise, Eq. (6) can be expressed as

$$P(\omega) = \frac{|V_{out}|^2}{2R} = \frac{N_0 + N_{-1}}{1 + \left|G(V_0)\right|^2 - 2G(V_0)\cos(\omega\tau - \varphi(\omega))} \tag{7}$$

where N_0 and N_{-1} are the power spectrum density of systematic white and flicker noise, respectively. Above equation can be further simplified as

$$P(\omega) = \frac{N_0}{2 - 2\cos(\omega\tau - \varphi(\omega))} + \frac{N_{-1}}{2 - 2\cos(\omega\tau - \varphi(\omega))} \tag{8}$$

At last, the single side band (SSB) phase noise of OEO can be expressed as

$$\begin{aligned} L(f) &= \frac{N_0/P_{OSC}}{2 - 2\cos(2\pi f\tau - \varphi(f))} + \frac{b_{-1,t}f^{-1}}{2 - 2\cos(2\pi f\tau - \varphi(f))} \\ &= \frac{b_{0,t}}{2 - 2\cos(2\pi f\tau - \varphi(f))} + \frac{b_{-1,t}f^{-1}}{2 - 2\cos(2\pi f\tau - \varphi(f))} \\ &= \frac{S_{\varphi,t}(f)}{2 - 2\cos(2\pi f\tau - \varphi(f))} \end{aligned} \tag{9}$$

where $S_{\varphi,t}(f)$ is link's phase noise, composed of white and flicker phase noise; $b_{0,t}$ is total white phase noise and $b_{-1,t}$ is total flicker phase noise coefficient of open-loop link.

Assuming that 6 km SMF-28 fiber is applied and the value of $b_{0,t}$ is about −140 dBc/Hz, the SSB phase noise of OEO as a function of offset frequency in different value of $b_{-1,t}$ is shown in Fig. 2. Four colored curves represent the SSB phase noise data of single-loop OEO with 6 km fiber at $b_{-1,t}$ of −120, −110, −100 and −90 dBc/Hz. The curves own high spurs due to small FSR caused by long fiber and the SSB phase noise increases with $b_{-1,t}$. In the case of low $b_{-1,t}$, the flicker noise makes influence on the near-DC phase noise, but if the flicker noise is high enough, the far-DC phase noise could be enhanced evidently.

4. Low phase noise MPL

Compared with traditional MPL, high-linear PD and low-phase noise amplifier are used to decrease the phase noise of MPL. A