Variable-linewidth light source based on Brownian motion random walk in optical phase

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Abstract We proposed a variable linewidth light source using random walk phase noise. As a demonstration, the impact of the laser linewidth on the error-vector magnitude performance in the optical QPSK transmission was evaluated by using the proposed laser source experimentally, where the linewidth tunable range was from 40 kHz to 5 MHz.

Keywords: linewidth, phase noise, phase modulation, random walk, digital coherent communication

Classification: Optical hardware (fiber optics, microwave photonics, optical interconnects, photonic signal processing, photonic integration and modules, optical sensing, etc.)

1. Introduction

Reduction of laser linewidth is required for sensing applications such as Coherent LiDAR [1, 2, 3, 4], as well as for digital coherent transmission systems [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15]. In general, narrow linewidth lasers would have long cavities and complicated configurations to stabilize the frequency and phase of the optical outputs. Thus, installation cost would be an issue in such systems with narrow linewidth lasers. Estimation of the required linewidth is needed to avoid the use of over-quality lasers. It would be rather difficult to tune the linewidth which is an intrinsic laser parameter, while the wavelength and output power can be easily controlled. Thus, many lasers which have variety of linewidths are required to measure the impact of the laser linewidth on performance of optical transmission and sensing systems [16, 17, 18, 19]. To accurately assess the impact of the linewidth, a variable-linewidth laser has been proposed and demonstrated, where the linewidth can be changed from 0.8 to 353 kHz [20]. In the proposal, the linewidth was controlled by a fiber stretcher placed the optical feedback loop. A drawback of the approach is that the spectrum shape changes depending on the linewidth. There is also an example of variable linewidth light sources using IQ modulation with a high frequency carrier [21]. However, the high-order harmonics are generated by the carrier component in the modulation signal. Thus, this technique is not suitable for estimation of linewidth requirement in digital coherent communication systems. In Raman amplifiers, the linewidth of the light source can be intentionally enlarged in order to suppress the effects of Brillouin scattering [22].

In this work, we propose a variable-linewidth light source that has the Lorentzian spectrum, with a tunable range from 40 kHz to 5 MHz, to emulate spectra of external cavity lasers (ECLs) and distributed feedback (DFB) lasers. In the future, vertical cavity surface emitting lasers (VCSELs) will be widely used for various applications including high resolution sensing. Thus, it will be necessary to support a wider linewidth tunable range, for characterization of optical systems with various lasers. A phase modulator whose half wave voltage is precisely measured in a mesofrequency range from a few kHz to 10 GHz broadens to a narrow linewidth light, without using any high frequency carrier component. A high-speed pseudo random number generator is fed to the modulator for phase noise generation. As a demonstration, the impact of the laser linewidth on error vector magnitude (EVM) in a digital coherent system was measured by using the variable-linewidth light source.

2. Theory

A method for increasing the linewidth by digital phase modulation is described.

When the phase noise $\phi(t)$ of light is modeled as the Brownian motion, the light would have a Lorentzian spectrum [23]. At this time, the variance $\langle \phi^2(t) \rangle$ of the phase noise is expressed by the following equation:

$$\langle \phi^2(t) \rangle = 2D|t|$$

where $2D$ is equal to the angular full linewidth at half maximum (FWHM) defined in Ref. [24]. Here we consider the following random walk with discrete Brownian motion. Random walk is a phenomenon in which the next appearing value appears randomly, and it is represented by the following recurrence formula:

$$\phi(t) = 0$$
\[
\phi(t + \Delta t) = \begin{cases} 
\phi(t) - \Delta \phi, & \text{probability 50}\% \\
\phi(t) + \Delta \phi, & \text{probability 50}\% 
\end{cases} \quad (3)
\]

where \(\Delta t\) is a time step of phase change, and \(\Delta \phi (> 0)\) is a phase change amount per time step. However, this phase change is sufficiently smaller than the phase change of the carrier wave. The coefficient \(D\) can be described by

\[
D = \Delta \phi^2 / 2\Delta t \quad (4)
\]
as shown in Eq. (2.29) of Ref. [25]. Therefore, the linewidth in frequency domain, which is defined by the over \(\Delta \phi^2 / 2\pi \Delta t\). The linewidth can be changed by phase-modulating a narrow linewidth light source with a noise signal that follows a random walk. However, according to Eq. (1), \((\phi^2(t))\) diverges with time, and the absolute value of often becomes very large. We may use the conventional phase wrapping process to limit the absolute value of the phase. However, rapid phase changes in the wrapping process can generate high-order harmonics, and it is generally difficult to accurately shift the phase by \(2\pi\).

To overcome this difficulty, we used mirror images of random walk processes. This is an operation that wraps around when a random walk reaches a certain value [26]. A random walk according to Eq. (2) and Eq. (3) is created, and around when a random walk reaches a certain value \([26]\). A random walk processes. This is an operation that wraps around when a random walk reaches a certain value [26]. A random walk according to Eq. (2) and Eq. (3) is created, and when the absolute value of \(|\phi(t)|\) reaches \(\phi_{th} (> 0)\) at time \(\tau\), the following operations are sequentially performed.

\[
\phi'(t) = \begin{cases} 
\phi(t), & t < \tau \\
-\phi(t) + 2\phi_{th}, & t \geq \tau 
\end{cases} \quad (5)
\]

Furthermore, \(\phi_{th}\) is an arbitrary value, so there is no need to shift the phase by \(2\pi\). As a result, \(\phi'(t)\) changes continuously, and high-order harmonics such as wrapped phase do not occur. The random walk process generated by this operation is also one of samples in random walk processes, the ergodic property is lost by this reflection operation, but if \(\phi(t)\) does not frequently reach \(\phi_{th}\), the influence appears only in the low frequency region.

3. Basic evaluation of variable-linewidth light source

The linewidth was increased by applying a noise signal to the phase modulator. Two fiber lasers (NKT photonics: Khoras Basik) were used as narrow linewidth light sources, as shown in Fig. 1. Linewidths of these fiber lasers were 100 Hz or less [27, 28]. The repetition frequency of the arbitrary waveform generator (AWG) was 10 kHz. The signal was amplified by a wideband amplifier (SHF Communication Technologies AG: SHF 115BP) with gain of 26 dB. The amplitude of the signal was adjusted by a tunable attenuator (Agilent: 8494A, 8495A, 11713A). To measure the half wave voltage of the lithium niobite (LN) phase modulator (Sumitomo Osaka Cement: T.PMH1.S-5.5-S), in a low frequency below 1 GHz, a signal generator was employed to replace the AWG, amplifier and the attenuator. In this experimental setup, a sinusoidal wave was applied to the modulator for a sideband generation. The half wave voltage was measured from ratios between the sideband components, as shown Fig. 2 [29, 30].

Fig. 3 shows the spectrum of the variable-linewidth light source when \(\phi_{th} / \Delta \phi\) was set as 50 and 100 while \(1/\Delta t\) was fixed at 10 GHz. These spectra were obtained by optically-heterodyne for the noise-modulated fiber laser and another fiber laser source. When \(\phi_{th} / \Delta \phi\) is small, the folding operation of the reflection principle occurs frequently. Thus, the low frequency components of the noise signal are lost. Consequently, the spectrum of the larger \(\phi_{th} / \Delta \phi\) became closer to the theoretical value. Based on Eq. (1), the linewidth is expanded by the square of the change in phase per unit time. Fig. 4 shows the relationship between \(\Delta \phi\) and the linewidth when \(1/\Delta t\) was fixed at 10 GHz. Our experimental setup shown Fig. 1 cannot generate low frequency components (<50 kHz), because it is limited by the repetition frequency of AWG and the cutoff frequency of the amplifier. The maximum linewidth is limited by the sampling frequency and the frequency response of the amplifier. In this experiment, the maximum linewidth is limited to 4.76 MHz because of
4. Demonstration of application to communications

By using the proposed a variable-linewidth light source, we measured the relationship between the linewidth of the optical carrier and the EVM performance in optical QPSK transmission as shown Fig. 5. For the receiver, we employ a modulation analyzer (Agilent: N4392A). The signal processing on the receiving side is the phase track by the Kalman filter and polarization detection [31]. The parameters for these algorithms are adjusted to minimize EVM without the linewidth tuning, carrier phase variance (parameter of Karman filter) is $5 \times 10^{-7}$. As suggested in the previous section, the variable-linewidth light source could not generate phase noise in the low frequency region, but, such low-frequency components have less impact on the system performance in practice owing to the phase tracking. As shown Fig. 6, the influence of a linewidth is measurable by changing a linewidth continuously from 40 kHz to 5 MHz. Because the constellation is like circle as shown Fig. 7, the noise of received signal is almost phase noise.

5. Conclusion

We proposed a variable-linewidth light source using optical phase modulation with random walk processes. The wavelength tunable range was from 40 kHz to 5 MHz. Mirror images of random walks were used to limit the signal amplitude for optical phase modulation. The low frequency part of the noise is lost in the mirror image generation process, but it would not have large impact on digital coherent detection. As a demonstration, we measured EVM of QPSK transmission with varying the linewidth of the light source. Low frequency noise, which would have significant impact on some sensing applications, can be generated by using analog noise sources or low frequency signal generators in addition to the signal source demonstrated in this paper.

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