A Novel Phase-Noise Cancelled Optical Frequency Domain Reflectometry Using Modulation Sidebands

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Abstract-**We propose a novel OFDR method which improves spatial resolution by cancelling laser phase noise. Laser light is modulated with linearly swept frequency. Both the backscattered light and the reference light are combined and divided into upper- and lower-sideband components by an optical filter. These two components are converted two electrical signals and multiplied each other. The laser phase noise which is contained these signals can be cancelled completely by this multiplication. The proposed method is confirmed experimentally. The laser phase noise having 1.5-MHz linewidth is cancelled by this method. These results confirm that this method is feasible to improve spatial resolution for OFDR.**

Keywords- Phase Noise; OFDR; Intensity-modulation; Modulation Sidebands

I. INTRODUCTION

Optical fibers have low loss and broadband properties. They are used for long-haul and huge capacity optical transmission systems. Moreover, optical fiber characteristics can be changed by the environment temperature and the pressure which applied to them. Therefore, optical fibers can be used for sensors.

Optical frequency domain reflectometry (OFDR) and optical time-domain reflectometry (OTDR) [1][2] are methods for measuring optical reflection points over fibers.

OTDR has been widely used to diagnose the break point of optical fibers. The spatial resolution of OTDR is limited by the pulse width used, and is about 1 to 10 m. OTDR is required to increase the optical power for long distance measurements.

On the other hand, OFDR observes beat signals which are produced by the reference light and the backscattered light at reflection points. The beat frequencies are proportional to the distances from the reflection points because the optical source frequency is linearly swept. OFDR has better spatial resolution and excellent sensitivity than OTDR. However, the OFDR measurement range is limited by the laser coherence length because laser phase noise causes serious degradation to the signal-to-noise ratio (SNR) as the measurement distance approaches the laser coherence length. The coherence length is about several tens of meter, because typical linewidth of DFB-LD is a few MHz. Therefore, it is impossible to apply this technique to transmission fibers.

Recently, the phase noise compensation OFDR (PNC-OFDR) on the concatenated reference method has been proposed [3]. By the PNC-OFDR, 20 km have been reported to achieve sub-meter range resolution measurements[4]. However, this method need additional reference arm, complicate signal processing and narrow linewidth optical source.

In this paper, we propose a novel phase noise cancelled OFDR method. The proposed method is modulated by linearly swept frequency with double sideband-suppressed carrier modulation. The backscattered light and the reference light are combined and divided into upper- and lower-sideband. The divided lights are detected and each signals are multiplied each other. Then the phase noise cancelled signals are obtained. We will demonstrate the proposed method to find break point. Next section, we will show the principle of the proposed phase noise cancelled OFDR method. Then we will show experimental results to confirm our proposed method.

II. PRINCIPLE

OFDR method has merits of high spatial resolution and high sensitivity. The spatial resolution ΔL is determined by $\Delta L = c/(2n_{fiber}\Delta f)$ where c is the light velocity in vacuum, n_{fiber} is the fiber refractive index and Δf is the sweep frequency range. For instance, if Δf =5 GHz, the spatial resolution ΔL =2 cm. But, its measuring range is limited by the coherence length. The coherence length l_c is calculated as $l_C = c/\delta f$ where δf is laser linewidth. For example, if the linewidth is 10 MHz, the coherence length is 30 m. It corresponds to the measuring length of 15 m. Therefore, it is impossible to measure long distance fiber. Then, the OFDR method is used for only defecting points of optical components.

We propose a novel phase noise cancelled OFDR method. Figure 1 shows the proposed configuration, schematically. Figure 2 shows the principle of phase noise cancellation. Although the light source frequency of the ordinary OFDR is swept by saw teeth, that of the proposed method is not swept. The light source is modulated with double sideband-suppressed carrier. The optical field $E(t)$ can be described as

$$\begin{aligned} E(t) &= E_0 \cos\left(\omega_m t + \pi\beta t^2\right)\cos\left\{\omega_C t + \theta\left(t\right)\right\} \\ &= \frac{E_0}{2}\left[\cos\left\{\omega_+ t + \pi\beta t^2 + \theta\left(t\right)\right\}\right. \\ &\qquad \left. + \cos\left\{\omega_- t - \pi\beta t^2 + \theta\left(t\right)\right\}\right] \end{aligned} \tag{1}$$

where $\omega_+ = \omega_C + \omega_m$, $\omega_+ = \omega_C - \omega_m$, ω_C is the carrier angular frequency, ω_m is the modulation angular frequency, β is the linear sweep rate, $\theta(t)$ represents the random phase resulted from phase noise.

The angular frequency of the first term is

$$\frac{\partial \phi_1}{\partial t} = \omega_c + \left(\omega_m + 2\pi\beta t\right) + \frac{\partial \theta(t)}{\partial t} \tag{2}$$

The angular frequency of the second term is

$$\frac{\partial \phi_2}{\partial t} = \omega_c - \left(\omega_m + 2\pi\beta t\right) + \frac{\partial \theta(t)}{\partial t} \tag{3}$$

The first term frequency increases with modulation frequency while the second term frequency decreases. However, the phase noise term is added to both frequency.

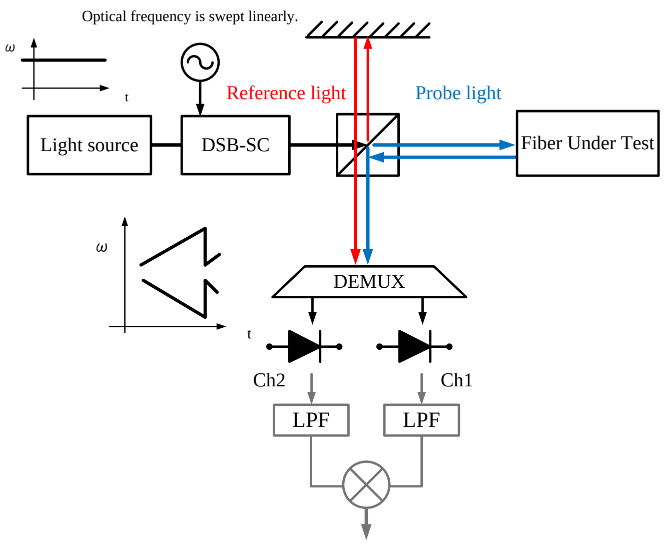


Fig. 1 Configuration of the proposed OFDR. DSB-SC: double sideband modulator, demux : optical demultiplexer

When the light source is modulated by the double sideband-suppressed carrier method, two sidebands appear as shown in Fig. 2(a). The modulated light is divided into two arms. One arm's light is for the reference light and acts as local oscillator light for heterodyne detection. The other arm is fed to fiber under test (FUT) to find the reflection points along the fiber. Rayleigh backscattered light from FUT is coupled with the reference light as shown in Fig. 2(b). The reflected light with the delay time τ_{FUT} is expressed as

$$E(t) = \frac{E_0}{2}\alpha\left[\cos\left\{\omega_+(t-\tau_{FUT}) + \pi\beta(t-\tau_{FUT})^2 + \theta(t-\tau_{FUT})\right\} + \cos\left\{\omega_-(t-\tau_{FUT}) - \pi\beta(t-\tau_{FUT})^2 + \theta(t-\tau_{FUT})\right\}\right] \tag{4}$$

where α represents the fiber loss and the reflectivity of the returned signal, the delay time $\tau_{FUT}=2L/v$, L is the fiber length and v is the light velocity in the fiber.

The combined lights are divided into two frequency components using the optical demultiplexer. The divided two components are detected with photo detectors and converted to electrical signals as shown in Fig.2(c).

The electrical signals are described without dc components as

$$\begin{aligned} I_1(t) &\propto \cos\{2\pi\beta\tau_{FUT} t + \theta(t) - \theta(t-\tau_{FUT}) + \varphi_1\} \\ I_2(t) &\propto \cos[2\pi\beta\tau_{FUT} t - \{\theta(t) - \theta(t-\tau_{FUT}) + \varphi_2\}] \end{aligned} \tag{5}$$

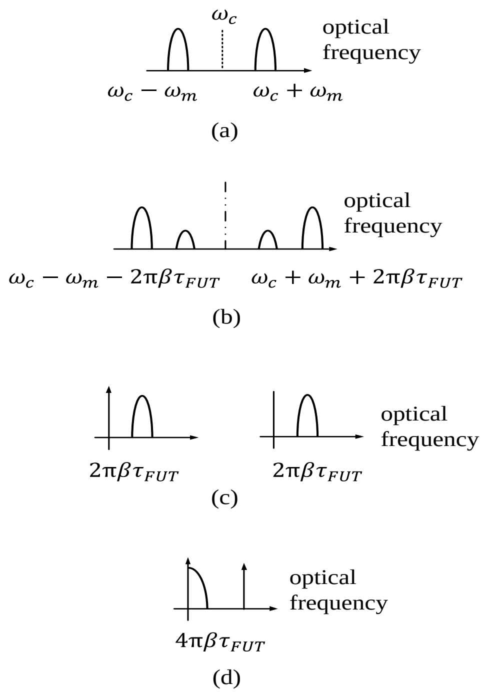


Fig. 2 Principle of the phase noise cancellation. (a) output spectrum from the modulator, (b) spectra reference light and signal, (c) detected electrical signal spectra and (d) multiplied spectrum.

Where $\varphi_1 = \omega_+\tau_{FUT} - \pi\beta\tau_{FUT}^2$, $\varphi_2 = -\omega_-\tau_{FUT} - \pi\beta\tau_{FUT}^2$. These frequencies are proportional to the delay time τ_{FUT}. Therefore, the reflected point can be known, but, they contain phase noise. The phase noise components are the opposite sign with the angular frequency $2\pi\beta\tau_{FUT}$.

By multiplying the two signals, take higher frequency component, then the signal is

$$I_1(t) \times I_2(t) \propto \cos\left(4\pi\beta\tau_{FUT} t + \varphi_1 + \varphi_2\right) \tag{6}$$

We can ignore the constant phase term $\varphi_1+\varphi_2$ for this measurement. The phase noise is completely cancelled by this process and the frequency components $2\beta\tau_{FUT}$ will appear.

If the light source frequency is swept linearly like OFDR, the modulated frequency and phase noise have the same sign and they cannot be cancelled. On the other hand, by our method, the sidebands frequencies are swept by the applied sweep signal. Then the both sidebands are spread and the sign has the opposite each other but the sign of the phase noise is the same. Then, the phase noise is cancelled by the multiplication.

The merits of the proposed method are simple configuration and this can cancel phase noise completely. Moreover, since two channel signals travel the same pass, stable detection can be realized because the two signals experience the same environments such as thermal disturbance, vibration and so on.

We confirm the proposed method by simulation. We assume that the light source has the linewidth of 1.5 MHz and modulated by the 160 GHz/s linear sweep rate ($\beta=1.6\mathrm{x}10^{11}$Hz/s). The signal light is passed through a delay fiber to apply constant delay with 126 μs ($\tau_{FUT}=1.26\mathrm{x}10^{-4}$s) which corresponds to 20 MHz beat frequency. The transmitted light is combined with the reference light. The combined lights are divided into two frequency components, that is, higher/lower frequency components compared with carrier frequency. The divided lights are detected and multiplied each other.

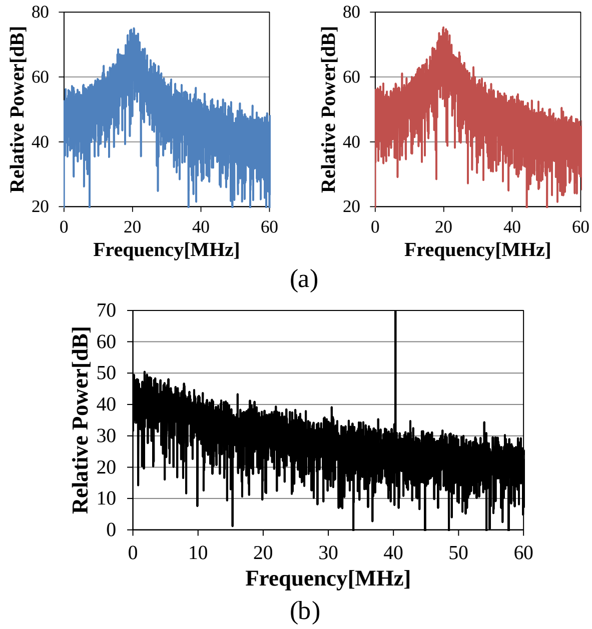


Fig. 3 Spectra for received at ch1 and ch2 (a) and multiplied of the two signal (b) at simulation

The simulated spectra are shown in Fig.3. Beat signals appears around 20 MHz which are broadened by phase noise as shown in Fig. 3(a) for each channel. The multiplied spectrum as shown in Fig. 3(b) shows sharp peak at around 40 MHz. This result shows the phase noise is completely cancelled by this process. A linewidth at 20 dB down from the peak in Fig.3 (b) is 40 kHz which is restricted by the sampling period.

The merits of this method are simple configuration and this can cancel phase noise completely and we can use normal DFB-LD.

III. EXPERIMENTAL SET-UP

The purpose of this experiment is to confirm the feasibility of the proposed method. First, we try to check a constant reflection point, next we measure the characteristics with OFDR configuration.

The experimental setup is shown in Fig.4. A Distributed Feed-Back (DFB)-laser diode with the linewidth of 1.5 MHz at 1550 nm is used as light source. The output is intensity-modulated by $LiNbO_3$ dual drive MZM intensity modulator. The double sideband-suppressed carrier modulation is performed by applying opposite phase signals to two arms which is described as

$$\begin{aligned} E(t) &= \sum_{n=-\infty}^{\infty} J_n(m)\cos(\omega_C + n\omega_m)t - \sum_{n=-\infty}^{\infty} J_n(m)\cos\{(\omega_C + n\omega_m)t + n\pi\} \\ &= \sum_{n=-\infty}^{\infty} \{1-(-1)^n\} J_n(m)\cos(\omega_C + n\omega_m)t \\ &= \cdots + 2J_{-3}(m)\cos(\omega_C - 3\omega_m)t + 2J_{-1}(m)\cos(\omega_C - \omega_m)t \\ &\quad + 2J_1(m)\cos(\omega_C + \omega_m)t + 2J_{-1}(m)\cos(\omega_C + 3\omega_m)t + \cdots \end{aligned}$$

where m is the modulation index.

The swept frequency signal is divided into two signals using 180 degree hybrid. The bias voltage of the modulator is adjusted so as to suppress the carrier component. The modulated optical spectrum with 12 GHz constant frequency modulation is shown in Fig.5. The carrier component is suppressed more than 18 dB down from the signal. The modulated light is amplified and divided into two arms. One is used for the local oscillator as the reference light. The other arm's light is used for the following two experiments.

A. *Confirmation of phase noise cancellation*

The other arm's light is fed to the fiber with the length of 25.2 km to clarify our proposed method in the first experiment. The modulation frequency is swept from 10 GHz to 15 GHz with 160 GHz/s average sweep rate. The reference light and the signal are combined. The combined lights are divided using arrayed waveguide grating(AWG) optical filter with 25 GHz channel spacing and 18 GHz bandwidth. The carrier frequency is set to the stop band(between two pass-band). Then, the first lower/upper sidebands will pass through AWG and output at adjacent ports. The outputs of the two ports are detected by photo detectors and sampled A/D converter(200 MS/s). The number of sampling points is 10,000, then the frequency step after FFT is 20kHz. The detected signals are multiplied each other. The spectrum of the multiplied signal is measured.

B. *Phase noise cancellation of Rayleigh backscatter signals*

In the second experiment, 25.2 km single-mode fiber is connected to the optical circulator as FUT. Moreover, 2 km single-mode fiber is inserted between the optical circulator and the coupler. This is because the fold back of the received spectrum decreases the performance in short distance. The modulation frequency is swept from 10 GHz to 15 GHz. Sweep rate is 29.6 GHz/s. The following setup is the same as first experiment.

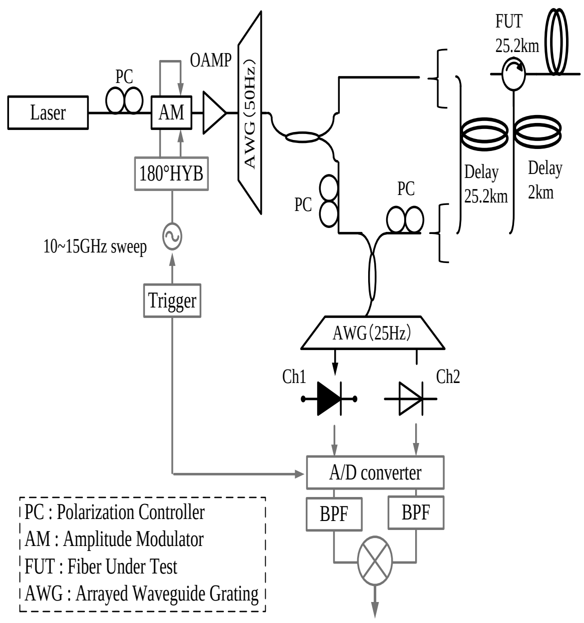


Fig. 4 Experimental set-up

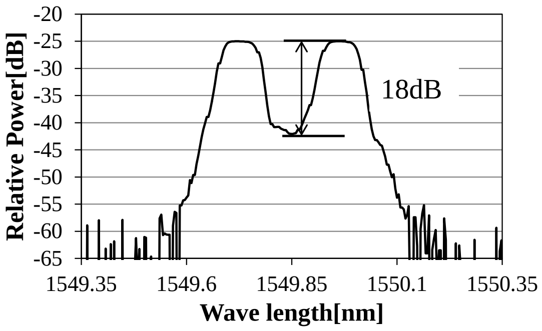
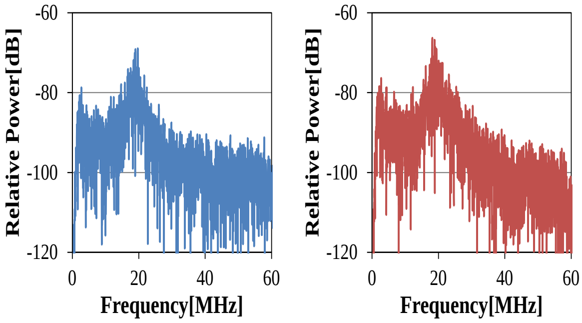


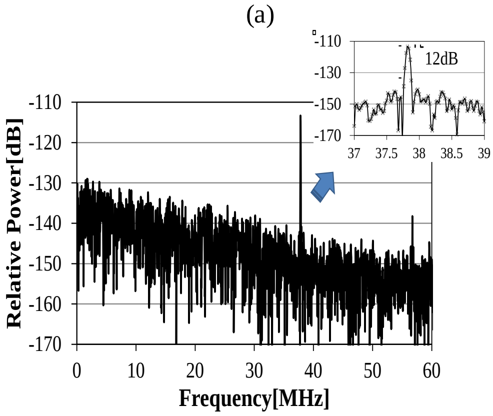
Fig. 5 Optical spectrum with double sideband-suppressed carrier modulation

IV. EXPERIMENTAL RESULT

The first experimental results are shown in Fig.6. Figure 6(a) is the spectra which are the individual arm and Fig. 6(b) is the multiplied spectrum with two arm signals. The sweep rate is 160 GHz/s and the fiber delay corresponds to 126 μs, then the beat frequency is appeared around 20 MHz including the phase noise. The spectra are broadened by phase noise. Figure 6(b) shows a sharp peak at around 40 MHz and noise level depressed by this multiplication. A linewidth at 20 dB down from the peak as shown in the inset of Fig.6 (b) is 120 kHz. The measured linewidth is broader than the simulated one. This is considered that the propagation time from the coupler to photo detectors is not same.



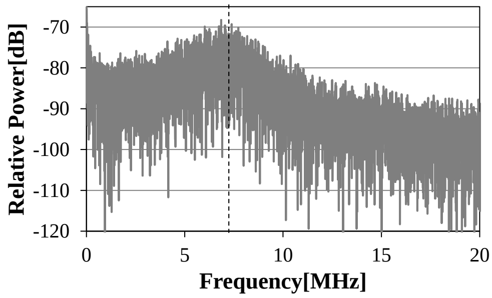
(a)



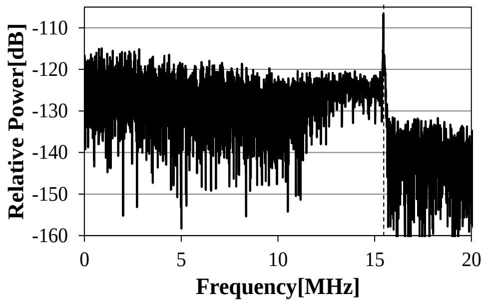
(b)

Fig. 6 Spectra for received at ch1 and ch2(a) and multiplied of the two signal(b)

Second experimental results are shown in Fig. 7. The divided phase-modulated light is fed to FUT which is 25.2 km single-mode fiber. The backscattered light is passed through 2km single-mode fiber to add the delay which is for



(a)



(b)

Fig. 7 Spectra for received at ch1 (a) and multiplied of the two signal (b)

the heterodyne detection. This light is detected as the previous experiment does. Figure 7(a) shows the detected spectrum at channel 1. There is a dull peak around 7.5 MHz. It is broadened by laser phase noise. The multiplied spectrum shown in Fig.7(b) has a Fresnel sharp peak at around 15 MHz. This means that the phase noise is completely cancelled by this method. Therefore, this spatial resolution can be improved.

V. CONCLUSION

We have proposed a novel OFDR method which improves spatial resolution by cancelling laser phase noise. Optical source with finite linewidth is phase modulated with modulation frequency sweep instead of sweeping the source frequency. The modulated signal is divided into the reference light and the test signal. The backscattered light and the reference light are combined and filtered to divide upper-sideband and lower-sideband. These two signals are detected and converted to electrical signals and multiplied each other. The output signal is phase cancelled. The proposed method is confirmed by the preliminary experiment. The laser phase noise having 1.5 MHz linewidth is cancelled by this method. This result confirming that this method is feasible to improve spatial resolution for OFDR.

We are going to investigate the characteristics of multiple reflection points.

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