Sub-cm Spatial Resolution Reflectometry over 10 km Based on Phase Noise Compensated OFDR with Third Order Sideband Sweeping

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Abstract *We describe PNC-OFDR employing 3rd order sideband sweeping to realize a broader frequency sweep span. We achieved a sub-cm spatial resolution over a 10 km measurement range.*

Introduction

Coherent optical frequency domain reflectometry (C-OFDR) with a high spatial resolution is an attractive technique for optical network maintenance [1]. However, the C-OFDR measurement range is limited by the light source coherence length. To extend the measurement range, we have already demonstrated C-OFDR employing an SSB modulator and a narrow linewidth fibre laser, and achieved a 3 cm resolution over a 5 km range [2]. Moreover, to realize a measurement range beyond the laser coherence length, we proposed phase noise compensated OFDR (PNC-OFDR) employing a concatenative reference method, and obtained a spatial resolution of 5 cm, which was the theoretical spatial resolution corresponding to a frequency sweep span of 2 GHz, over 10 km [3-4].

A broader frequency sweep span is needed to improve the spatial resolution. However, this is limited by the quality of the RF signal inputted into the modulator for the sweeping. With the commonly used RF synthesizer, it is difficult to sweep the RF signal frequency over a bandwidth of more than a few GHz without signal interruption owing to the switching of various electrical modules in the synthesizer. The concatenative reference method does not work well with such signal interruptions. Therefore, the spatial resolution of conventional PNC-OFDR has been limited to several cm.

In this paper, we demonstrate a new scheme for improving the spatial resolution by expanding the optical frequency sweep span of PNC-OFDR. We show that a 3rd order sideband is generated by employing two $LiNbO_3$ intensity modulators (LN-IM) arranged in series as the external modulator. And the optical frequency sweep span becomes three times broader than that of conventional PNC-OFDR. Based on the scheme, we demonstrate sub-cm spatial resolution measurement over a 10 km range with PNC-OFDR adopting the 3rd order sideband sweeping.

Principle of 3rd-order sideband sweeping

The conventional PNC-OFDR technique, which has been described elsewhere, uses a 1st order sideband for external frequency sweeping. If we can use a higher order sideband as the test light, the spatial resolution will be improved because of the broader optical frequency sweep span. Two LN-IMs are arranged in series to generate only ±3rd order sidebands. First, the input lightwave is modulated by RF signals of $\phi_1\sin\Omega t$ and $-\phi_1\sin\Omega t$, and also given a phase difference of 0 by applying DC bias voltages at the first LN-IM. Then, at the second LN-IM, the lightwave is modulated by RF signals of $\phi_2\sin\Omega t$ and $-\phi_2\sin\Omega t$, and given phase difference of π. ϕ_1 and ϕ_2 are modulation indexes, and Ω is the angular frequency of the RF signal. Thus, when sidebands higher than 5th order are neglected, the output of the optical field $E_{out}(t)$ is expressed as

$$E_{out}(t) = e^{i\omega t}J_1(\phi_2)\Big[\{J_0(\phi_1)-J_2(\phi_1)\}e^{i\Omega t}+\{J_2(\phi_1)-J_4(\phi_1)\}e^{i3\Omega t} + \{J_2(\phi_1)-J_0(\phi_1)\}e^{-i\Omega t}+\{J_4(\phi_1)-J_2(\phi_1)\}e^{-i3\Omega t} + J_4(\phi_1)e^{i5\Omega t}-J_4(\phi_1)e^{-i5\Omega t}\Big] ,(1)$$

where ω is the angular frequency of the lightwave, and $J_n(\phi_x)$ is a first order Bessel function. Here, when ϕ_1=1.84, $J_o(\phi_1)$-$J_2(\phi_1)$=0. Therefore, the terms of ±1st order sidebands in Eq. (1) disappear. Note that ±5th order sidebands still exist but they are negligible because the ratio of the amplitudes of the ±5th and ±3rd order sidebands ($J_4(\phi_1)/J_2(\phi_1)-J_4(\phi_1)$) is 0.08 when ϕ_1=1.84. When applying this scheme to PNC-OFDR, Ω must be linearly swept with respect to time. Therefore, Ωt in Eq. (1) is expressed as $\Omega(t)=2\pi f_m t+\pi\gamma t^2$, where f_m and γ are the initial value of the modulation frequency and the frequency sweep rate of the RF signal, respectively. Finally, the output of the optical field is simply given as follows;

$$E_{out}(t) = e^{i\omega t}J_1(\phi_2)\Big[\{J_2(\phi_1)-J_4(\phi_1)\}e^{i(6\pi f_m t+3\pi\gamma t^2)} + \{J_4(\phi_1)-J_2(\phi_1)\}e^{-i(6\pi f_m t+3\pi\gamma t^2)}\Big] .(2)$$

In this way, only ±3rd order sidebands are strongly generated and swept by a very simple configuration consisting of two LN-IMs. From Eq. (2), the optical frequency sweep rate and sweep span of the 3rd order sideband become three times higher than that of the inputted RF signal. Therefore, the spatial resolution of PNC-OFDR with a 3rd order sideband is three times greater than that of conventional PNC-OFDR.

Experimental set-up

Figure 1 shows the experimental set-up for PNC-OFDR. We used a fibre laser with a narrow linewidth

(Ethernal[TM], Orbits Lightwave, Inc.) as the optical source. The RF signal from the RF synthesizer was inputted into a 3rd order sideband generator with two LN-IMs throughout a phase shifter, which was used for adjusting the modulation timing, and swept from 10 to 16 GHz for a 23 ms acquisition time. Therefore, the frequency sweep rate γ of the RF signal was 260 GHz/s, and the frequency sweep span ΔF of the RF signal was 6 GHz. Based on above discussion, the optical frequency sweep rate γ_{opt} and sweep span ΔF_{opt} of the 3rd order sideband became 780 GHz/s and 18 GHz, respectively. Therefore, the theoretical spatial resolution Δz_{min} was improved to 5.5 mm by employing the 3rd order sideband. The modulated lightwave was inputted into an optical filter to eliminate the -3rd order sideband, and then we were able to obtain a single sideband spectrum. The suppression ratio between the +3rd order sideband and the other sidebands of the spectrum was 10-20 dB over the entire modulation bandwidth. The modulated lightwave was divided and input into the main interferometer, which contained the fibres under test (FUTs), and the auxiliary interferometer. The auxiliary interferometer with a 5 km-long delay fibre was used to compensate for the laser induced phase noise with a concatenative reference method [5]. The delay fibre in the auxiliary interferometer was placed in a soundproof box to insulate it from environmental acoustic noise [3]. In our experiments, the total sound level was 57 dB (14 mPa). The beat signals from the main and auxiliary interferometers were detected and then acquired with a 12-bit analog digital converter (A/D) at a sampling rate of 200 MHz. The beat signal data were sent to a personal computer for numerical processing with the concatenative reference method. The FUTs were 5, 6.25, 7.5, 8.75 and 10 km long. The far ends of the FUTs were an angled PC connector (APC).

Experimental results

Figure 2 shows spectra of the reflection at 10 km. The red and blue lines show the reflection spectrum with and without compensation, respectively. These results were obtained by averaging ten spectra. By the compensation, the phase noise was considerably reduced, and the two reflections were clearly separated. After the compensation, the spatial resolution based on the full width at half maximum (FWHM) was 8 mm. The concatenative reference method realizes the best compensation at integer multiple positions of the delay fibre length in the auxiliary interferometer. In contrast, at the boundary positions of the compensated section, the effect of the compensation is degraded. In our experiment, 5, 7.5 and 10 km are the best compensation positions, and 6.25 and 8.75 km are boundary positions. Therefore, we investigated the spatial resolutions at those positions as shown in Fig. 3. The spatial resolution under a sound noise level of 57 dBm achieved a sub-cm spatial resolution over a 10 km range although the boundary positions were included. This means that the concatenative reference method for PNC-OFDR with 3rd order sideband sweeping worked very well over a 10 km range. Under a higher total sound level of 62 dB (25 mPa), the sub-cm spatial resolution was almost maintained with only the spatial resolution at 8.75 km reaching 150 mm. The sensitivity (relative to the Rayleigh backscattering level) was about -25 dB for all measurements.

Conclusions

We demonstrated sub-cm spatial resolution reflectometry over a 10 km range based on PNC-OFDR employing two LN-IMs arranged in series for a broader external frequency sweeping with a 3rd order sideband. The sensitivity (relative to the Rayleigh backscattering level) was about -25 dB for all measurements. It appears to be almost impossible to realize both a sub-cm spatial resolution and a sensitivity of -25 dB simultaneously over 10 km with any conventional reflectometry technique.

References

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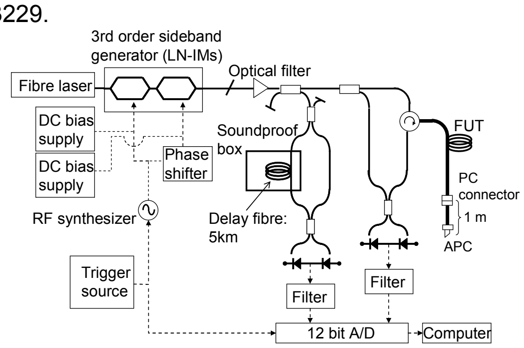

Fig. 1 Experimental set-up

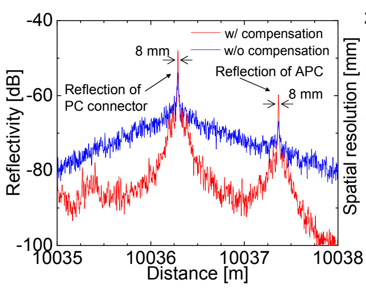

Fig.2 Reflection spectra around 10 km point

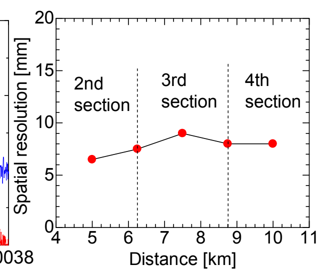

Fig. 3 Spatial resolutions of reflection events at different distances.