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Dual frequency probe based coherent optical time domain reflectometry

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ABSTRACT

A new approach to enhance the performance of coherent optical time domain reflectometry(C-OTDR) is proposed. In this approach, single frequency light is converted to multi-frequency light using phase modulator (PM), while only two frequencies with the same light power level are adopted as the probe .Coherent heterodyne between the dual frequency probe and original single frequency local oscillator (LO) generates the same intermediate frequency (IF), which equals two IF signals automatically synthesizing in the process of coherent detection other than in IF signal processing circuit, so it doubles measurement speed. Experimental results show that compared with conventional single frequency probe based C-OTDR the dual frequency probe based C-OTDR has more quickly coherent Rayleigh noise (CRN) reduction capability and can bring a 3.0 dB dynamic range improvement.

1. Introduction

Optical time domain reflectometry (OTDR) is a commonly used instrument for fiber characterization and fault location in optical transmission systems [1]. With use of coherent detection technique, weak backscattered power can be attained to near quantum limit of photodetector. Thus it greatly improves the dynamic range of OTDR. As the linewidth of probe light used in C-OTDR is usually below 10 kHz, it unavoidably causes strong CRN [1,9,10], which degrades the smoothness of OTDR trace and furthermore influences event identification accuracy. Additionally, the narrow linewidth probe light has low stimulated Brillouin scattering (SBS) threshold, which is a main disadvantage that limits dynamic range enhancement of C-OTDR [8]. For CRN reduction and dynamic range enhancement, most commonly used method is to increase measurement and average times [3–8]. As COTDR is mainly used in long haul multi-fiber span undersea optical transmission line monitoring, it may take several hours to perform an effective monitoring task. So speeding up its measurement process is highly significant and practical.

Considering the problems above, for further enhancement of C-OTDR performance, we propose a new dual frequency probe based approach, which employs a PM to convert single frequency light into multi-frequency light with three frequencies of the highest power: 0 and ± 1order, while two frequencies of the three are adopted as the probe. Coherent heterodyne between the backscattered Rayleigh signals from FUT and the original single frequency LO generates the same IFs, which equals two IF signals automatically synthesizing in the coherent detection process. That's to say by the new approach measurement speed is double of conventional single frequency probe based C-OTDR, so according to statistic theory [9], it doubles CRN reduction efficiency. On the other hand, for multi-frequency light generated by PM probe power is allocated to many frequencies, which improves SBS threshold by 5.2 dB at PM modulation depth of 1.44 demonstrated in Ref. [2]. Therefore, by this new approach the maximum probe power can be double of conventional single frequency based probe, so the new dual frequency probe based C-OTDR can bring a 3.0 dB dynamic range enhancement.

2. Generation of multi-frequency light by PM

When light with angular frequency of ω passes through PM, it will be converted to multi-frequency light with equal frequency separation [2]. It can be expressed as,

$$E = \sqrt{P_0}\exp(j\omega t)\sum_{q=-\infty}^{\infty} J_q(A_m)\exp(jq\omega_m t) \tag{1}$$

where $\sqrt{P_0}$ is amplitude of output light from PM before modulation, ω is the original angular frequency of input light, ω_m and A_m are modulation angular frequency and modulation depth of PM respectively and q is frequency order of the multi-frequency light with value of 0, ± 1, ± 2…. The power configuration of the main frequencies output from PM in different modulation depth is shown in Fig. 1. As can be seen from Fig. 1 ,when the modulation depth is 1.44, three frequencies—0, ± 1 orders have the same magnitude, each taking up 30% of the total output light power, which also means 5.2 dB lower than the total output light power. At this modulation depth, the SBS threshold of probe light can be enhance by 5.2 dB, which is

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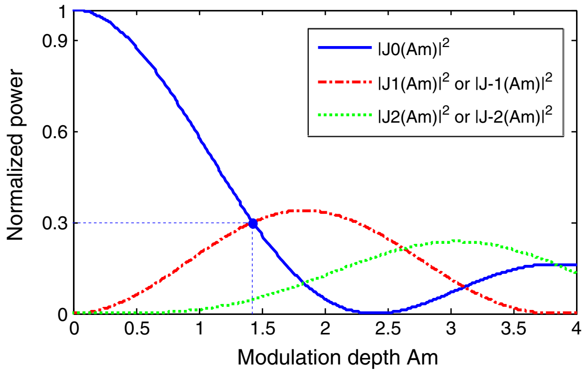

Fig. 1. Power configuration of output light from PM at different modulation depth.

experimentally demonstrated in Ref. [2], as a result it brings a 3.0 dB dynamic range increase in our dual frequency probe based C-OTDR.

Through heterodyne with original single frequency light, we precisely obtained the three frequency orders with PM modulation depth of 1.44 and modulation frequency of 10 MHz, shown in Fig. 2. The power configuration of each frequency order fits the theoretical value quite well.

3. Principle of the dual frequency probe based C-OTDR

Fig. 3 illustrates a schematic diagram of C-OTDR using multi-frequency probe light. External cavity laser diode (ECLD) with narrow linewidth of 3.7 kHz generates light with wavelength of 1561.42 nm. The laser from ECLD is split into two paths by a 90/10 coupler. The one with higher power is used for the probe light and the other is used as LO. The state of polarization (SOP) of the probe light is adjusted to make insertion loss of PM minimal. The modulation depth of PM is fixed at 1.44, so the output power of PM concentrates on three frequencies—0 and ±1order as shown in Fig. 2 .Then the multi-frequency light is amplified by EDFA and its power is adjusted by variable optical attenuator (VOA) to make each of the three frequencies have the same power level with that in the condition of single frequency probe light interaction, so as to conduct performance comparison of the two approaches: conventional single frequency probe based C-OTDR and the new dual frequency probe based one. The probe pulse is generated by acousto-optic modulator (AOM) and polarization scrambled by polarization scrambler (PS) and then launched into the first port of circulator. Then the probe pulse is launched into the fiber under test (FUT) through the second port of circulator. The FUT is consisted of two fiber sections with length of 24.91 km and 49.46 km respectively. At last its backscattered Rayleigh light output from the third port of the circulator is combined with LO in a 3 dB coupler. A balanced photodetector (BPD) receives IF signals generated in coherent detection process and outputs corresponding current signals.

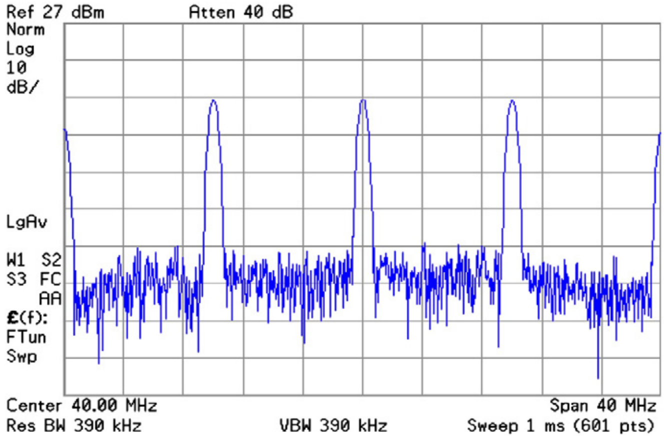

Fig. 2. Frequency orders and power configuration of output light from PM obtained by heterodyne method.

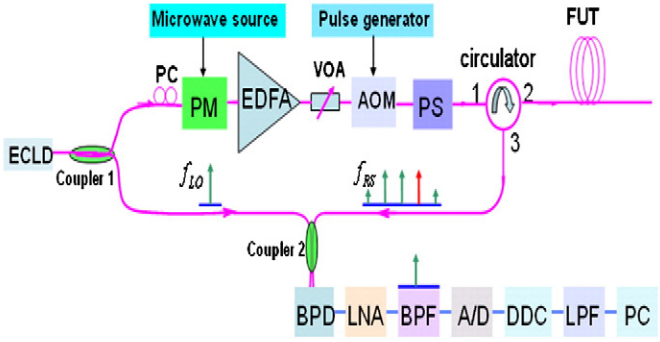

Fig. 3. New C-OTDR setup using dual-frequency probe light.

Coherent detection involves combining a low level signal field E_{sig} with a higher power LO E_{LO}, and for multi-frequency probe light this process is written as,

$$E_{total} = E_{sig} + E_{LO} \tag{2}$$

As the power of backscattered Rayleigh signals of the multi-frequency probe light is quite weak, the heterodyning among them can be omitted. Then the output current of photodetector can be expressed as,

$$\begin{aligned} i &= \left|E_{sig} + E_{LO}\right|^2 \\ &= R\cdot\left\{\left|E_{LO}\right|^2 + \sum_{q=-n}^{n}\left|E_{sig}^{q}\right|^2 + 2E_{LO}\cdot\sum_{q=-n}^{n}E_{sig}^{q}\cos(q\cdot\omega_{PM} + \Delta\omega_{AOM})t\right\} \end{aligned} \tag{3}$$

By BPD we can directly get the AC term at its AC port, and the AC term can be written as,

$$i_{AC} = 2R\cdot E_{LO}\cdot\sum_{q=-n}^{n}E_{sig}^{q}\cos(q\cdot\omega_{PM} + \Delta\omega_{AOM})t \tag{4}$$

When modulation depth of PM is 1.44, according to Eq. (4) the three dominant IF components can be written as,

$$i_{IF} = 2R\cdot E_{LO}\cdot\sum_{q=-1}^{1}E_{sig}^{i}\cos(q\cdot\omega_{PM} + \Delta\omega_{AOM})t \tag{5}$$

Where R is responsivity of BPD, q is frequency order of multi-frequency light, ω_{PM} is modulation angular frequency of PM, and $\Delta\omega_{AOM}$ is angular frequency shift of AOM.

As AOM used in experiment has a 40 MHz frequency up shift, we set modulation frequency of PM at 80 MHz, so the three dominant frequencies are $f_0 - 40$ MHz, $f_0 + 40$ MHz and $f_0 + 120$ MHz, where f_0 is the original frequency generated by ECLD. We only use the first two frequencies as the probe, so coherent heterodyne between the probe and LO with original frequency f_0 generates two IF signals of 40 MHz, which means two IF signals automatically synthesizing in heterodyne process other than in the IF signal processing circuit in Ref. [7,8]. Then the current signals are amplified by a low noise amplifier to increase its power for analog to digital converting (ADC). Before ADC IF signals with frequency of 40 MHz are filtered out by a bandpass filter (BPF) to improve signal to noise ratio (SNR), which is a remarkable characteristic of C-OTDR. Generally the bandwidth of BPF is inversely proportional to probe pulse width, so for probe