Development of Polarization Diversity Sampling Head Unit using Organic AANP Crystals and 160 Gb/s Far-end Waveform Measurement

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Keywords : optical sampling oscilloscope, short optical pulse, 160 Gb/s, KTP crystal, AANP crystal, a polarization-independent optical sampling head

It was reported that 2-adamantylamino-5-nitropyridine (AANP) crystal, which is a new developed organic crystal, could be applied to the high sensitive optical sampling head over C-band (1530 to 1565 nm). But the precious characteristics of the AANP was not well known.

So we studied the precious characteristics of AANP crystal and the expanding thechnology for wavelength range of the optical sampling head unit using this crystal. Futhermore we developed the assembling technique of a polarization diversity sampling head unit for polarization independent mesuring waveforms based on this studies.

This paper reports the characteristics of an AANP crystal for OSO, a developed configuration of a polarization diversity sampling head unit. we will demonstrate 160 Gb/s far-end measurement using a polarization-independent optical sampling head unit.

We evaluated the relationship between the normalized conversion efficiency and polarization state for incident light. The result confirms that the conversion efficiency range of the AANP crystal can be expanded by setting the optimum polarization. Then we evaluated the conversion efficiency for three different incident angles of $+1^\circ$, 0° , -1° around an incident angle of 90° . The result confirms that the wavelength with peak efficiency can be adjusted to the C-L bands using the AANP surface incident light angle, because the peak efficiency shifted to the long wavelength range at a -1° incident angle, and to the short wavelength range at a $+1^\circ$ incident angle.

These results show that we can build a high-sensitivity optical sampling head unit covering the C-L bands using the above assembly technique and an AANP crystal.

Figure 1 shows the characteristics of the AANP conversion efficiency of the prototype polarization diversity sampling head unit and the KTP conversion efficiency of a traditional polarization dependent sampling head unit. The SFG conversion efficiency of the AANP in the developed polarization diversity head unit is 20 times higher than the traditional sampling head using KTP over the C-L bands, and the 3 dB wavelength bandwidth is two times wider.

Figure 2 shows the result of far-end measurement of a 160Gb/s waveform after 5 km transmission using this head. It confirms that the OSO with prototype polarization diversity head can

measure post-transmission signal waveforms stably in spite of changing polarization state in an optical transmission fiber frequently. Because an eye diagram waveform for RZ signal is opened clearly.

Fig. 1. Characteristics of AANP conversion efficiency in prototype polarization diversity head and KTP efficiency in traditional sampling head

Fig. 2. Far-end waveform of 160 Gb/s signal after 5 km transmission measured by OSO with polarization diversity head

Development of Polarization Diversity Sampling Head Unit using Organic AANP Crystals and 160 Gb/s Far-end Waveform Measurement

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Abstract: We have previously developed a turn-key-ready OSO (optical sampling oscilloscope) system with a jitter of 0.2 ps rms and a resolution of 1 ps. Recently, we studied the characteristics of an AANP (2-adamantylamino-5-nitropyridine) crystal, which is the newest organic crystal for achieving a high-sensitivity optical sampling head unit for the OSO system. We developed a polarization-independent sampling head with a high sum-frequency conversion efficiency over the C-L bands using the AANP crystals.

This paper reports the characteristics of the AANP crystal and the developed configuration of a polarization-independent optical sampling head unit with AANP crystals. Furthermore, we demonstrate 160 Gb/s far-end measurement using the OSO system with the developed sampling head unit.

Keywords : optical sampling oscilloscope, short optical pulse, 160 Gb/s, KTP crystal, AANP crystal, polarization-independent optical sampling head

1. Introduction

An optical sampling oscilloscope (OSO) system is very useful for waveform measurement of ultra-high-speed-bit-rate optical signals, because it can correctly measure waveforms with low timing jitter and high temporal resolution. Previously, we reported a short optical pulse generation technique with 0.5ps pulse width and low timing jitter using an electro-absorption modulator (EAM) and a dispersion decreasing fiber (DDF)⁽¹⁾. We also developed a turn-key-ready OSO system with a KTP (KTiOPO4) optical mixer based on these techniques which are insensitive to ambient perturbations⁽²⁾.

However this developed OSO system has some problems. It was not realized enough performances although an OSO system is generally requested high sensitivity, polarization independency and wide wavelength range with C-L bands (1530 to 1610 nm).

Dr. Takara et.al. have proposed to apply the 2-adamantylamino-5-nitropyridine (AANP) crystal, which is a new developed organic crystal with a high non-linear coefficient, to an optical mixer for improving sensitivity in C-band (1530 nm to 1565 nm)⁽³⁾.

So we studied the AANP crystal characteristics and technology for expanding the wavelength range of the sampling head unit. In addition, based on the study, we considered assembly and configuration techniques for polarization-independent waveform measurement.

Section 2 of this paper introduces the arrangement and basic principles of the optical sampling system. In addition, Section 3 reports the AANP characteristics and Section 4 describes a developed polarization diversity sampling head unit. Section 5 demonstrates 160Gb/s far-end measurement using a polarization-independent optical sampling head unit. Finally, Section 6

summarizes the conclusions.

2. System Arrangement and basic Principles of Optical Sampling

Figure 1 shows a schematic diagram for optical sampling. Basically, an OSO system is composed of an optical sampling pulse generator, a polarization combiner such as a polarization beam splitter (PBS), an optical mixer for generating the cross-correlation signal, an avalanche photo-detector (APD), a CPU and a monitor.

The optical sampling pulse generator outputs a very short optical pulse train. Both the DUT signal and optical sampling pulse are combined in the polarization combiner and inserted to the optical mixer on the same optical axis. The optical mixer is used as an optical sampler under the type-2 phase-matching condition.

The optical mixer generates a sum-frequency generation (SFG) signal with a power that is proportional to the cross-correlation intensity between the DUT signal and optical sampling pulse.

The power of the SFG signal, P_{SF} , is given by equation:

$$P_{SF} = \eta_{sfg} \cdot P_{sig} \cdot P_{sam} \quad \dots \dots \dots (1)$$

where, η_{sfg} is the conversion efficiency of the optical mixer, P_{sig}

Fig. 1. Schematic diagram of optical sampling

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Fig. 2. Timing chart of sampling pulse and DUT signal

is the power of the DUT signal at the sampling point, and P_{sam} is the peak power of the sampling pulse. After this power of the SFG signal is converted to an electrical signal by the APD and processed by the CPU, the DUT signal waveform is displayed on the monitor.

Therefore, the sensitivity of the OSO system is dependent on η_{sfg} . Making use of high- η_{sfg} materials for the system is very important.

Figure 2 shows the timing chart for the sampling pulse and DUT signal.

The relationship between the sampling pulse and DUT signal is given by equation:

$$\frac{1}{f_s} - \frac{N}{f_0} = \Delta T \quad (2)$$

where, f_s is the repetition frequency of the sampling pulse, f_0 is the repetition frequency of the DUT signal, N is the sample number, and ΔT is the delay time every sampling.

The waveform, which is represented by an envelope of a peak power for a cross correlation signal, is magnified in the time domain compared to the DUT signal waveform.

The magnification factor, S_0 , is given by equation:

$$S_0 = \frac{1}{f_0 - Nf_s} \quad (3)$$

As the results, the ultra-high-speed-bit-rate optical signal waveform can be measured easily in a low frequency range by setting N to a large value and a sampling repetition frequency to low.

3. AANP Characteristics

This section describes the characteristics of the AANP crystal to obtain the best suitable assembly technique for the sampling head unit. Figure 3 shows the crystal shape and the a-, b-, and c-axis for an evaluation AANP with a phase-matching angle of 1552 nm. First, we evaluated the relationship between the normalized conversion efficiency and polarization state for incident light (Fig. 4). The data were obtained by changing the DUT signal wavelength from 1530 to 1570 nm (C-band) at a fixed sampling pulse wavelength of 1552 nm and keeping the incident angle of 90°. Open squares (□) are data for the AANP crystal when the polarization direction of the optical sampling pulse is parallel to the a-axis and the polarization direction of the DUT signal is parallel to the b-c surface. Solid circles (●) are data for the

Fig. 3. Optical incident angle and crystal axes of AANP

Fig. 4. Relationship of normalized conversion efficiency and polarization state for incident light

AANP crystal when the polarization direction of the optical sampling pulse is parallel to the b-c surface and the polarization direction of the DUT signal is parallel to the a-axis.

The results show that the conversion efficiency range of the AANP crystal can be expanded by setting the optimum polarization state for each incident optical signal.

Next, We evaluated the relationship between the normalized conversion efficiency and incident angle. Figure 5 shows the conversion efficiency for three different incident angles of +1°, 0°, -1° around an incident angle of 90°. These data were obtained by rotating around the a-axis and changing the wavelength of the DUT signal from 1530 to 1570 nm (C-band) with the sampling pulse wavelength fixed at 1552 nm.

The result confirms that the wavelength with peak efficiency can be adjusted to the C-L bands using the AANP surface incident light angle, because the peak efficiency shifted to the long wavelength range at a -1° incident angle, and to the short wavelength range at a +1° incident angle.

From above results, we find that we can build a high-sensitivity optical sampling head unit covering the C-L bands by improving the assembly technique for an AANP crystal.

Fig. 5. Relationship of normalized conversion efficiency and the incidence angle

Fig. 6. Relationship of normalized conversion efficiency and incident beam waist of prototype optical sampling head

Next, for evaluating influence on a normalized conversion efficiency by a beam waist size, we built a type-2 experimental optical sampling head (Fig. 6) covering the C-L bands with a changed beam waist size using the above assembly method, because the intensity of the non-linear light generation depends on the power focused by an optical lens.

The result confirms that we can build an optical sampling head using an AANP crystal with a beam waist size of less than 36 μm for the C-L bands. Consequently, we decided to use a focusing lens to achieve a beam waist of 20 μm , because this condition is optimum for manufacturing and considering thermal reliability of the sampling head unit in the C-L bands.

4. Configuration of Polarization Diversity Sampling Head Unit

This section describes the developed sampling head unit. Figure 7 shows the configuration of a diversity sampling head unit composed of a polarizer, a polarization beam splitter (PBS), two TiO_2 crystals (polarization combiners), a $\lambda/2$ -wave plate, two AANP crystals, two infrared cut filters, and two APDs. The polarizer and PBS split the sampling pulse into two sampling

Fig. 7. Configuration of developed polarization diversity sampling head unit

Fig. 8. Characteristics of AANP conversion efficiency in polarization diversity head and KTP conversion efficiency of traditional sampling head

pulses of equal power. The DUT signal is split into two DUT signals according to the polarization. The polarization combiners (two TiO_2 crystals) combine one sampling pulse and one DUT signal with orthogonal polarization and high polarization extinction ratio. The $\lambda/2$ -wave plate between the PBS and second polarization combiner compensates for the relative difference in the length of the optical path between the sampling pulse and DUT signal. Without it, the relative length between the sampling pulse and DUT signal is different for each combiner, causing degraded temporal resolution of the OSO system. The combined sampling pulse and DUT signal with orthogonal polarizations to each other is input to an AANP crystal. The beam waist size is set to 20 μm . The a-axis of the AANP crystals

Fig. 9. Overview of prototype polarization diversity sampling head unit

are arranged parallel to the direction of the sampling pulse. The incident angle is adjusted to cover the C-L bands. The difference in the SFG conversion efficiency between AANP1 and AANP2 causes polarization dependency, so the amplitude of the two APDs output signals are adjusted to compensate by adjusting the ratio of the electrical amplifier.

Figure 8 shows the characteristics of the AANP conversion efficiency in the polarization diversity sampling head unit and the KTP conversion efficiency of a traditional polarization dependent sampling head unit. The SFG conversion efficiency of the AANP in the developed polarization diversity head unit is 20 times higher than the traditional sampling head over the C-L bands, and the 3 dB wavelength bandwidth is two times wider.

Figure 9 shows an overview of the prototype polarization diversity sampling head with expanded wavelength range. The head size is $70 \times 70 \times 15$ mm.

5. Evaluation of OSO with Polarization Diversity Sampling Head

This section explains the results of an evaluation experiment on OSO with the prototype polarization diversity head unit.

AANP crystals have some individual difference of SFG conversion efficiency like Figure 8. This difference was adjusted to be the same sensitivity at 1570 nm by using the electrical gain control circuit in the OSO for reducing polarization dependency.

Figures 10 (a)(b) show the measured waveforms for a 40 Gb/s RZ signal with a pulse width of 2 ps and the same peak power. Figure 10(a) is the eye-diagram waveform for 1550 nm; Figure 10(b) is for 1610 nm. This measured waveforms show that the wavelength range of this head unit cover the C-L bands. Because the waveform at 1550 nm and the waveform at 1610 nm are almost same.

Fig. 11 shows a polarization dependency measurement result at 1550 nm. The polarization dependency (fluctuation width) is suppressed to $\pm 3\%$ though the two-polarization sensitivity is adjusted at 1570 nm. This shows that the sensitivity of this sampling head has good flatness at C-L band wavelength range. We think this fluctuation can be reduced to almost zero by using software calibration etc.

Figure 12 shows the result of far-end measurement of a 160 Gb/s waveform after 5 km transmission using the OSO with this head. It confirms that the OSO with prototype polarization

(a) Wavelength of DUT signal: 1550 nm (b) Wavelength of DUT signal: 1610 nm

Fig. 10. Waveforms of 40 Gbps RZ signal with pulse width of 2 ps

Fig. 11. Polarization dependency of OSO system with prototype polarization diversity sampling head (Wavelength of DUT signal: 1550 nm)

Fig. 12. Far-end waveform of 160 Gb/s signal after 5 km transmission measured by OSO with polarization diversity head

diversity head can measure post-transmission signal waveforms stably in spite of changing polarization state in an optical transmission fiber frequently. Because an eye diagram waveform for RZ signal is opened clearly.

6. Conclusion

We evaluated the conversion efficiency of an AANP crystal and studied a method for using it in an OSO optical sampling head.

In addition we designed a polarization diversity sampling head. We found high conversion efficiency over the C-L bands. The 3 dB down-band range can be obtained between 1530 and 1610 nm by using an AANP cut for 1552 nm phase matching.

To evaluate the characteristics of the OSO with polarization diversity sampling head, we measured the eye-diagram of the 40 Gb/s pulse for waveforms at 1550 and 1610 nm. Finally, we were able to stably measure the waveform of a PRBS7 modulated 160 Gb/s optical signal after transmission. These results confirm that we have successfully developed a polarization diversity sampling head covering the C-L bands.

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