Reducing the backreflection impact by using homodyne detection in WDM single-fiber loopback access networks

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Abstract: This paper uses homodyne detection to reduce the impact of backreflections in wavelength division multiplexing (WDM) single-fiber loopback access networks. We present the principle of our beat noise suppression scheme and the configuration of upstream signal transmission that enhances the effectiveness of the proposed technique. We also experimentally confirm that beat noises can be eliminated within the signal bandwidth with no significant waveform distortion.

Keywords: optical access network, bidirectional transmission, back-reflection, homodyne detection, WDM

Classification: Fiber-optic communication

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1 Introduction

The rapid growth of the Internet is strengthening demands for broadband services in access networks. To satisfy these demands, the introduction of wavelength division multiplexing (WDM) technologies is one of the most attractive solutions. For access networks that use WDM technologies, a wavelength-independent optical network unit (ONU), namely the colorless ONU, is the key technical issue. So far, many colorless ONUs that use wavelength supply schemes have been reported [1, 2]. These papers assume that upstream transmission is realized by a continuous wave (CW) light supplied from a central office (CO) to each ONU which modulates it and sends it back to the CO. However, these schemes suffer a serious problem in that the signal-to-noise ratio (SNR) is degraded by the beat noises caused by backreflection lights. To reduce the impact, several techniques that use frequency conversion to more than twice the clock frequency of the data signal have been proposed [3, 4].

This paper proposes a novel technique to reduce the backreflection impact in WDM single-fiber loopback access networks. Unlike [3, 4], we eliminate the beat noises within the signal bandwidth with the use of homodyne detection. The principle of this beat noise suppression scheme and the configuration of the upstream signal transmission to boost the effectiveness are explained and the feasibility of the proposed technique is experimentally confirmed.

2 Principle of proposed technique

When the supplied wavelength from the CO to the ONU is modulated by a data signal with the function of $f(t)$ and its frequency is shifted by f_m , the electrical field of the upstream modulated signal can be represented by $f(t)E_S \exp[i\{2\pi(f + f_m)t + \phi_S\}]$. Similarly, we can represent that of the reflected CW light in the transmission fiber as $E_R \exp[i(2\pi ft + \phi_R)]$. Here, f and ϕ are the frequency and the phase noise of the laser-diode (LD) used, respectively. When the upstream signal is received by direct direction, the output photo current is given by

$$i_p \cong f(t)^2 E_S^2 / 2 + f(t) E_S E_R \cos\{2\pi f_m t + (\phi_S - \phi_R)\}, \quad (1)$$

where we ignore some terms with small values for simplicity. The first term and the second term are the received signal and the interference beat noise between the modulated signal and the backreflection light, respectively. The second term is spread from DC to the clock frequency of the data signal (B). Therefore, the beat noises can not be eliminated by using an electrical filter unless a large f_m ($f_m \gg B$) is applied to exclude the noises outside the signal bandwidth [3, 4].

Fig. 1 shows the configuration of the proposed upstream transmission scheme. To reduce the impact of the backreflections, we apply homodyne detection. A tapped LD output and an optical 90° hybrid are used as a local light and a phase diversity module for homodyne detection, respectively. Unlike direct detection, a small frequency shift f_m ($B \gg f_m$) is applied

Fig. 1. Configuration of upstream signal transmission single-fiber loopback access networks using proposed beat noise suppression technique.

to the supplied wavelength using a frequency shifter (FS) to prevent the received signal carrier from being notched by AC coupling, i.e. DC block, which allows the homodyne receiver to implement envelope detection (either linear or square) [5]. When we represent the electrical field of the local light as $E_L \exp[i(2\pi f t + \phi_L)]$, the output photo currents of the two output ports of the optical 90° hybrid are given by

$$i_{p(0)} \cong f(t) E_L E_S \cos\{2\pi f_m t - (\phi_L - \phi_S)\} + E_L E_R \cos(\phi_L - \phi_R), \quad (2)$$

$$i_{p(\pi/2)} \cong f(t) E_L E_S \sin\{2\pi f_m t - (\phi_L - \phi_S)\} - E_L E_R \sin(\phi_L - \phi_R). \quad (3)$$

Each of the first terms is utilized to obtain the final received signal which is independent of f_m and ϕ by calculating the squared sum of these terms in digital signal processing (DSP) circuits. The second terms are the beat noises between the local light and the backreflection light. Unlike Eq. (1), the beat noises between the modulated signal and the backreflection light are not described here, because the values of these terms are negligible when the power of the local light is relatively large. As shown in these equations, the beat noise spectra of the second terms lie around DC because both the local light and the backreflection light are not modulated. Therefore, we can expect that most of the beat noises can be eliminated by using high pass filters (HPFs) whose cutoff frequency (f_c) are much lower than B ($B \gg f_m > f_c$). The noise spectral density, namely relative intensity noise (RIN), is expressed as a function of the position of the reflection point from the optical receiver in the CO (L) and the total amount of the beat noises which degrades the signal quality can be estimated by integrating the RIN within the signal bandwidth [6]. Fig. 2 shows the calculation results of the integral value of RIN (δ^2) against L given $B = 1.25$ GHz and LD linewidth (Δf) = 100 kHz. Here, E_S and E_R are set to the same value and DC blocks with f_c of 1 MHz, 10 MHz, and 100 MHz are used as HPFs. δ^2 of 0 dB shows that the beat noise power equals to the mark level power of the modulated signal. To regard the power penalty induced by the beat noises as negligible, δ^2 should be under -30 dB [7]. As shown in the figure, even when a DC block with f_c of 100 MHz

Fig. 2. Integral value of RIN (δ^2) against position of reflection point (L) in calculation.

is used, L must be over 2000 m to meet this guideline. Here, L of 2000 m is the coherence length of the LD used. In actual systems, reflection points may exist at positions close to the optical receiver in the CO. Therefore, to boost the effectiveness of the proposed technique, we place an optical delay line which is longer than the coherence length of the LD in the local light path as a phase correlation canceller.

For the proposed technique we should note that the HPFs may degrade the received signal waveform by filtering its spectrum. Therefore, it is preferred that we choose a data signal format that has no low frequency components, i.e. the gigabit Ethernet (GbE) signal format.

3 Experiments

To confirm the principle of the proposed technique, we conducted eye pattern measurements. The CW light output from a LD was divided by a 1 : 1 coupler to create the first loop for signal and the second loop for backreflection. In the first loop, the divided light is frequency-shifted by 120 MHz using an acousto-optic frequency shifter (AOFS), passed through a 40 km standard single mode fiber (SMF), and then modulated by a LiNbO₃ (LN) intensity modulator with a 1.25 Gb/s data signal. A $2^7 - 1$ pseudo random bit sequence (PRBS) is used because we assume GbE signal transmission. On the other hand, in the second loop, the divided light passes through a 20 km SMF after its power is attenuated by a variable attenuator (ATT). The two lights passing through these two loops are combined by another 1 : 1 coupler with their polarizations matched against each other by polarization controllers (PCs). The third loop for the local light is also created by dividing the LD output using a 1 : 10 coupler. This local light and the signal light (with the backreflection light when required) are input to an optical 90° hybrid with their polarizations matched against each other and the two outputs from the optical 90° hybrid are sampled by A/D conversion using a real time digital oscilloscope (OSC). The retrieved data are used to calculate eye diagrams. According to the results of the noise estimation in the previous chapter, DC

Fig. 3. Measured eye diagrams. (a-1) By direct detection, w/o backreflection. (a-2) By direct detection, w/ backreflection. (b-1) By homodyne detection, w/o backreflection, w/o DC block. (b-2) By homodyne detection, w/o backreflection, w/ DC block. (b-3) By homodyne detection, w/ backreflection, w/o DC block. (b-4) By homodyne detection, w/ backreflection, w/ DC block.

blocks with f_c of 100 MHz are inserted when required. The input powers into the PIN photodiodes of the signal and local lights are -37 dBm and $+2$ dBm, respectively. The power of the backreflection light is set to 6 dB lower than that of the signal light. As predicted in the previous chapter, the received signal is not degraded under this condition. The coherence length of the LD used is 2000 m ($\Delta f = 100$ kHz) and the lengths of three loops are 20 km different from each other. Therefore, although no optical delay lines are placed in the local light loop, the optical phases through these loops are completely random.

As reference data, we also measured the eye diagrams yielded by direct

detection using an avalanche photo diode (APD). In these measurements, the APD was placed between the 1 : 1 coupler and the optical 90° hybrid. Furthermore, the AOFS was replaced with an ATT to keep the output power from the 1 : 1 coupler constant. Fig. 3 (a-1) and (a-2) show the measured results. As shown in these figures, compared to the clear eye diagram observed when the backreflection loop was disconnected, the eye diagram with the backreflection loop was severely degraded due to the backreflection condition. Fig. 3 (b-1), (b-2), (b-3), and (b-4) shows the measured results for homodyne detection. Fig. 3 (b-1) and (b-2) are the cases without the backreflection loop. As shown in these figures, although the mark level in Fig. 3 (b-2) is slightly degraded compared to that in Fig. 3 (b-1) due to spectrum filtering by the DC blocks, good eye opening was observed. Fig. 3 (b-3) and (b-4) are the cases with the backreflection loop. As shown in these figures, compared to the measured eye diagram in Fig. 3 (b-3), which was severely degraded due to the beat noise by the backreflection light, a much better eye diagram, comparable to that in Fig. 3 (b-2), was obtained by using the DC blocks.

4 Conclusion

We proposed a novel beat noise suppression technique for WDM single-fiber access networks that use wavelength supply schemes. Our technique uses homodyne detection so the dominant beat noises caused by backreflections are concentrated around DC and these noises are eliminated by using electrical HPFs. A small frequency shift, which is much less than the clock frequency of data signal, is applied in the ONU to allow envelope detection in a homodyne receiver through the use of a phase diversity module. According to our noise estimation, an optical delay line which is longer than the coherence length of the LD should be placed in the local light path to boost the effectiveness of the proposed technique. We conducted eye diagram measurements on a 1.25 Gb/s data signal with $2^7 - 1$ PRBS, a frequency shift of 120 MHz, and DC blocks with cutoff frequency of 100 MHz, and confirmed that the proposed technique could suppress the beat noises with no significant signal degradation.