A Low-Crosstalk Design of 1.25 Gbps Optical Triplexer Module for FTTH Systems

Sung-il Kim, Suntak Park, Jong Tae Moon, and Hai-Young Lee

In this paper, we analyzed and measured the electrical crosstalk characteristics of a 1.25 Gbps triplexer module for Ethernet passive optical networks to realize fiber-to-the-home services. Electrical crosstalk characteristic of the 1.25 Gbps optical triplexer module on a resistive silicon substrate should be more serious than on a dielectric substrate. Consequently, using the finite element method, we analyze the electrical crosstalk phenomena and propose a silicon substrate structure with a dummy ground line that is the simplest low-crosstalk layout configuration in the 1.25 Gbps optical triplexer module. The triplexer module consists of a laser diode as a transmitter, a digital photodetector as a digital data receiver, and an analog photodetector as a cable television signal receiver. According to IEEE 802.3ah and ITU-T G.983.3, the digital receiver and analog receiver sensitivities have to meet -24 dBm at BER=10^{-12} and -7.7 dBm at 44 dB SNR. The electrical crosstalk levels have to maintain less than -86 dB from DC to 3 GHz. From analysis and measurement results, the proposed silicon substrate structure that contains the dummy line with 100 µm space from the signal lines and 4 mm separations among the devices satisfies the electrical crosstalk level compared to a simple structure. This proposed structure can be easily implemented with design convenience and greatly reduce the silicon substrate size by about 50 %.

Keywords: Dummy line, EPONs, triplexer, module, crosstalk, FTTH.

I. Introduction

Recently, the growing demand for multimedia applications has required an economical network system configuration and large-scale integration of highly accurate analog circuits with many high-speed digital circuit gates. In electrical module design, miniaturization is certainly very effective for reducing module costs, but it leads to a potential increase of electrical crosstalk. In subscriber network systems, a passive optical network (PON) is expected to be an economical way for future multimedia services networks [1].

In a PON system, there are two signal multiplexing schemes. One of them is the time-division-multiplexing (TDM) PON, which combines the signals from many subscribers serially in the time domain in a single channel without interfering with other signals by allocating unique time slots to each user within the channel. The second scheme is the wavelength-division-multiplexing PON, which allows wavelength-division multiplexing of the signals form each subscriber in parallel into a single channel by allocating a unique transmission wavelength to each user. The WDM-PON system is not yet well-commercialized because it requires relatively high-cost optical devices to allocate a unique transmission wavelength to each user. The control of multi wavelength channels is not easy.

Accordingly, the TDM-PON system has been well standardized by the Institute of Electrical and Electronics Engineers (IEEE) and the International Telecommunication Union-Telecommunication Standardization (ITU-T) sectors. In particular, the IEEE 802.3ah standardization sector has proposed a concept of Ethernet passive optical networks (EPONs) [2]. The EPON system is well recognized as a potentially useful fiber-to-the-home (FTTH) system.

The demand for high-quality multimedia services including

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high definition television, cable television (CATV), and video-on-demand services is increasing, and thus requires a triplexer-type optoelectronic transceiver module consisting of a duplexer-type optoelectronic transceiver module for digital communications and a high-performance analog photoreceiver for broadcasting services.

Generally, a 1.25 Gbps optical triplexer module with a planar light-wave circuit (PLC) has a configuration composed of a PLC-type WDM filter, laser-diode (LD), digital photodiode (D-PD), and analog photodiode (A-PD) on a silicon (Si) substrate. The PLC-type WDM filter distributes or combines a light-wave signal; the LD transmits a 1.25 Gbps electro-optic modulated signal; and the D-PD and A-PD receive a 1.25 Gbps optical modulated digital signal and an optical modulated CATV signal, respectively.

Electrical crosstalk can cause near field electro-magnetic interference (EMI) between closed signal lines or components [3]-[6]. Therefore, electrical crosstalk of the 1.25 Gbps optical triplexer module formed on a resistive Si substrate is more serious than crosstalk on a dielectric substrate. The reason for this is that the Si substrate has a lower resistivity than the dielectric substrate [7], [8].

According to the IEEE802.3ah standards, the data rate and digital receiver sensitivity of the gigabit optical transceiver module are specified to be 1.25 Gbps and –24 dBm@10^{-12} bit-error rate (BER), respectively [2]. ITU-T 983.3[9] and Telecommunication Technology Association Standard in Korea KO-07.0020 [10] specify the analogue receiver sensitivity to be –7.7 dBm @44 dB signal-to-noise ratio (SNR). Accordingly, the electrical crosstalk between an LD and D-PD has to less than –86 dB within the frequency range of 0 to 1.25 GHz to satisfy the sensitivity of the IEEE 802.3ah standard. Also, the electrical crosstalk between a D-PD and A-PD has to be less than –86 dB within the frequency range of 0 to 3 GHz to satisfy the sensitivity of the ITU-T G.983.3 and TTA standards.

Therefore, for large-scale-integration systems, the electrical crosstalk characteristics become very important for the optoelectronics on a PLC platform because the LD/D-PD/A-PD full-triplex operation is necessary in a gigabit PON system. There has been no report on the crosstalk characteristics of a 1.25 Gbps optical triplexer module with PLC platforms on a lossy Si substrate.

Consequently, we analyze the electrical crosstalk phenomena by proposing a Si substrate structure with a dummy ground line that corresponds to the simplest low-crosstalk layout configuration in a 1.25 Gbps optical triplexer module.

In this paper, we have designed a 1.25 Gbps optical triplexer module on the proposed Si substrate structure with the help of a three-dimensional structure simulator based on the finite element method. From our experimental measurements of the designed module, we have found that the electrical crosstalk between the LD and D-PD in a triplex gigabit optical transceiver is less than –86 dB in the frequency range of 0 to 1.25 GHz. The electrical crosstalk between the D-PD and A-PD is less than –86 dB in the frequency range of 0 to 3 GHz. Also, we have inserted a dummy ground line besides the D-PD signal and A-PD signal lines in order to decrease the electrical crosstalk. Therefore, the proposed Si substrate structure that contains a dummy ground line with 100 μm space from the signal lines and a 4 mm device separation satisfies the electrical crosstalk level comparably to a simple structure. This proposed structure can be easily implemented with design convenience, and can be used to deliver a greatly reduced Si substrate size by about 50 % [3].

II. Low-Electrical Crosstalk Design of the 1.25 Gbps Optical Triplexer Module

1. A Scheme of 1.25 Gbps Optical Triplexer Module

Figure 1 shows a 1.25 Gbps optical triplexer module configuration with a PLC for single-fiber EPONs. The 1.25 Gbps optical triplexer module is composed of a PLC with WDM filters, LD, D-PD, and A-PD on a resistive Si substrate. The first WDM filter transmits a 1.49 μm /1.3 μm wavelength signal and reflects a 1.55 μm wavelength signal. The second WDM filter transmits a 1.3 μm wavelength signal and reflects a 1.49 μm wavelength signal.

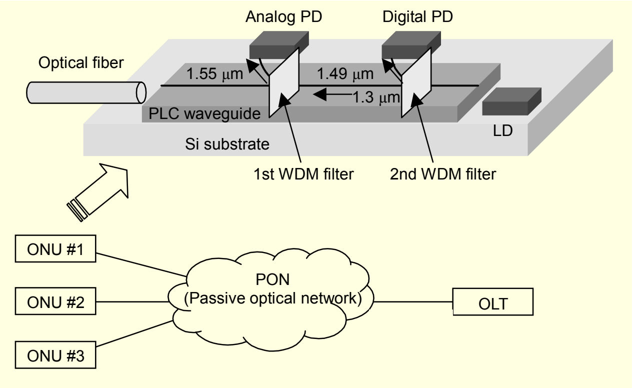

Fig. 1. 1.25 Gbps optical triplexer module configuration.

For full-triplex operation of the 1.25 Gbps optical triplexer module, suppression of the optical and electrical crosstalk is extremely important because the LD, D-PD, and A-PD are mounted on a resistive Si substrate with PLC platform. In this paper, the electric resistivity of the Si substrate is assumed to be 2000 Ωcm. The optical crosstalk can be well suppressed by placing a thin-film WDM filter [11], [12] among the LD, D-PD, and A-PD on the Si substrate. However, the electrical crosstalk is very difficult to suppress because it depends on the dimension of the module [3], [4], and [6]. Therefore, a design technique for suppressing the electrical crosstalk is required to obtain the receiver sensitivity and to decrease the module size for full-triplex operations.

2. Electrical Crosstalk Analysis

Since a low electrical crosstalk is crucial for full-triplex operations with high sensitivity, the electrical crosstalk levels have to be estimated to meet the standard requirement.

Electrical crosstalk is a near-field electromagnetic phenomenon. Electrical crosstalk depends on the distance between devices. Therefore, we have first considered the electrical crosstalk between closely located devices, such as between the LD and D-PD, and between the D-PD and A-PD. The electrical crosstalk between the LD and A-PD is negligible because the distance between them is longer than the distance between the LD and D-PD. Also, the electrical crosstalk occurs between a high-speed signal line and low-speed signal line. The high-frequency fringing field caused by a high-speed signal interferes with the low-speed signal line. Due to this high-frequency fringing field, the low-speed signal transmission characteristics are degraded. According to the international and domestic standards [2], [9], and [10], the digital receiver is operated up to 1.25 Gbps and the analog receiver is operated up to 155 Mbps. Therefore, in this paper we have considered the electrical crosstalk from the D-PD to A-PD.

Accordingly, Fig. 2 shows a circuit model of the electrical crosstalk phenomena. We have assumed that the voltage produced by the electrical crosstalk between the LD and D-PD ($Cx_{LD\text{-}DigitalPD}$) acts as the noise of the input signal to the preamplifier, and the current produced by the electrical crosstalk between the D-PD and A-PD ($Cx_{DigitalPD\text{-}AnalogPD}$) acts as the noise of the input signal to the low-noise amplifier (LNA). Also, we have neglected the electrical crosstalk between the LD and A-PD because the electrical crosstalk is highly dependent on the nearest component [4], [6].

Therefore, the electrical crosstalk between the LD and D-PD can be presented as in [8] by the SNR,

$$SNR = \frac{I_{ph-DigitalPD}}{\sqrt{I_n^{\ 2} + \left(\frac{V_{n-cx}}{R_{in,preamp}}\right)^2}}, \tag{1}$$

where $I_{ph\text{-}DigitalPD}$, I_n, $V_{n\text{-}cx}$, and $R_{in,preamp}$ are the averaged photocurrent due to the digital-modulated input optical signal into the D-PD, the noise current of the preamplifier, the noise voltage due to electrical crosstalk, and the input resistance of the preamplifier, respectively. To achieve an error-free operation of the receiver at BER=10^{-12}, an SNR of over 14.13 is required [13]. Hence, the noise voltage due to the electrical crosstalk between the LD and D-PD for error-free operation at BER=10^{-12} is represented as

$$V_{n-cx} = \sqrt{\left(\frac{I_{ph-DigitalPD}^{\ \ 2}}{14.13^2} - I_n^{\ 2}\right) \times R_{in,preamp}^{\ \ 2}}\ . \tag{2}$$

Then, the maximum electrical crosstalk between the LD and D-PD for error-free operation at BER=10^{-12} ($Cx_{LD\text{-}DigitalPD}$) is given by

$$Cx_{LD-DigitalPD} = 20\log\frac{V_{n-cx}}{V_{LD}}, \tag{3}$$

where, V_{LD} is the peak-to-peak value of the modulation voltage signal. Figure 3 shows the calculated maximum electrical crosstalk with the receiver sensitivity at BER=10^{-12} as a parameter of the amplitude of the modulation voltage signal, V_{LD}. In this calculation, we assume that the responsivity of the D-PD, the input resistance of the preamplifier, and the noise current (I_n) [8] are 0.9 A/W, 1.2 kΩ, and 30 pA/(Hz)$^{1/2}$, respectively.

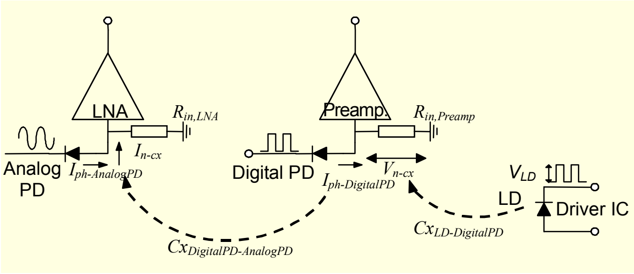

Fig. 2. Electrical crosstalk model of 1.25 Gbps optical triplexer module inductor and package parasitic.

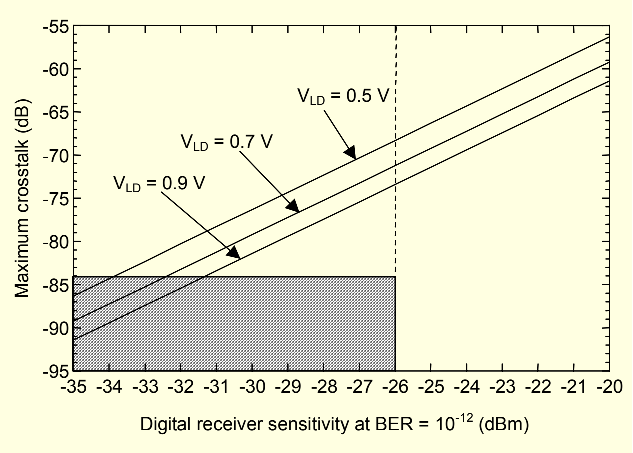

Fig. 3. The electrical crosstalk between the LD and D-PD with the receiver sensitivity at BER=10^{-12}.

In IEEE 802.3ah, a receiver sensitivity of under –24 dBm is specified for EPONs, which corresponds to about –26 dBm when the internal optical loss is considered in the module. After consideration of the additional noise in the module, we have decided on a target of electrical crosstalk suppression between the LD and D-PD to be less than –86 dB within the frequency range of 0 to 1.25 GHz, which is the D-PD operation range.

Using an analog receiver SNR and a noise figure (N.F.) of the LNA, the electrical crosstalk between the D-PD and A-PD can be presented by

$$I_{n-cx} = \frac{I_{ph-AnalogPD}}{SNR + N.F.}, \qquad (4)$$

where $I_{n\text{-}cx}$, $I_{ph\text{-}AnalogPD}$, SNR, and $N.F.$ are the noise current due to the electrical crosstalk between the D-PD and A-PD, the averaged photocurrent due to the analog-modulated input optical signal into the A-PD, the signal-to-nose ratio of the analog receiver, and the noise figure of the LNA, respectively. Hence, the electrical crosstalk between the D-PD and A-PD for the -7.7 dBm receiver sensitivity at 44 dB SNR in analog CATV service and –13.6 dBm receiver sensitivity at 28 dB SNR [9], [10] ($Cx_{DigitalPD\text{-}AnalogPD}$) is represented as

$$Cx_{DigitalPD-AnalogPD} = \frac{I_{n-cx}}{I_{ph-DigitalPD}}. \qquad (5)$$

Figure 4 shows the maximum electrical crosstalk between the D-PD and A-PD with the receiver sensitivity as the averaged photocurrent of the D-PD ($I_{ph\text{-}DigitalPD}$) and CATV services. In this calculation, we have assumed that the responsivity of the A-PD and the noise figure of the LNA are 0.9 A/W and 3.5 dB, respectively. In this figure, $I_{ph\text{-}DigitalPD}$ = 2.7 mA and $I_{ph\text{-}DigitalPD}$ = 2.5 μA are the maximum photocurrent and minimum photocurrent of the D-PD based on IEEE 802.3ah.

In the CATV standards, a receiver sensitivity of under –7.7 dBm @ SNR = 44 dB is specified for digital CATV service, and a receiver sensitivity of under –13.6 dBm @ SNR = 28 dB is specified for analog CATV service. These correspond to about –9.7 dBm and –15.7 dBm when considered with the internal optical loss in the module. From Fig. 4, we observe that the case of the analog CATV service with $I_{ph\text{-}DigitalPD}$ = 2.7 mA was the worst case in view of electrical crosstalk between the D-PD and A-PD. The reason for the electrical crosstalk is corresponded by the photocurrent of the D-PD. After consideration of the additional noise in the module, we decided on a target of electrical crosstalk suppression between the D-PD and A-PD to be less than –86 dB in the frequency range of 0 to 3 GHz, which is the A-PD operation range.

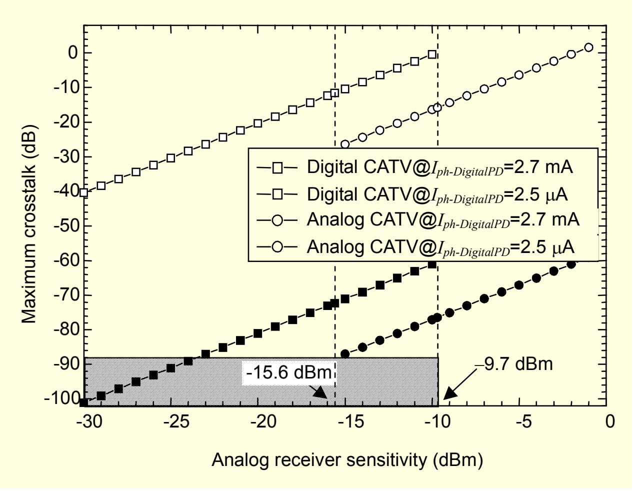

Fig. 4. The electrical crosstalk between the D-PD and A-PD with a receiver sensitivity applicable to CATV services.

Consequently, using a three-dimensional structure simulator based on the finite element method, we have analyzed the electrical crosstalk phenomena in a conventional 1.25 Gbps optical triplexer module, and proposed a low electrical crosstalk scheme with a dummy ground line structure. Figure 5 shows the electrical crosstalk analysis model used and the simulated results. In this figure, Dummy GND is the dummy ground line for reducing the electrical crosstalk. Distances S_1 and S_2 are the distances between the LD and D-PD, and between the D-PD and A-PD, respectively.

The electrical crosstalk analysis model for the three-dimensional structure simulator is shown in Fig. 5(a). We have analyzed the electrical crosstalk with the distance (S_1 and S_2) and the dummy ground effect. The reason for the electrical crosstalk in the 1.25 Gbps optical triplexer module depends on the distance (S_1 and S_2) between the LD and D-PD, and between the D-PD and A-PD. Therefore, we have shown the electrical crosstalk simulation results with S_1 and S_2 in Fig. 5(b).

In Fig. 5(b), since the Si substrate contains the dummy ground lines (dummy ground structure), $Cx_{LD\text{-}DigitalPD}$ with S_1 is the electrical crosstalk between the LD and D-PD with the LD-DPD distance (S_1), and $Cx_{DigitalPD\text{-}AnalogPD}$ with S_2 is the electrical crosstalk between the D-PD and A-PD with the D-PD-A-PD distance (S_2). Since the Si substrate does not contain the dummy ground lines (conventional structure), $Cx_{LD\text{-}DigitalPD}$ w/o Dummy GND @ S_1=4 mm is the electrical crosstalk between the LD and D-PD without dummy ground lines at S_1 = 4 mm, and $Cx_{DigitalPD\text{-}AnalogPD}$ w/o Dummy GND @ S_2 = 4 mm is the electrical crosstalk between D-PD and A-PD without dummy ground lines at S_2 = 4 mm.

From the simulation results, when decreasing S_1 and S_2, the electrical crosstalk is increased due to an increase of the fringing field effect as the distance between components decreases. We can obtain an electrical crosstalk of under –86 dB in the dummy

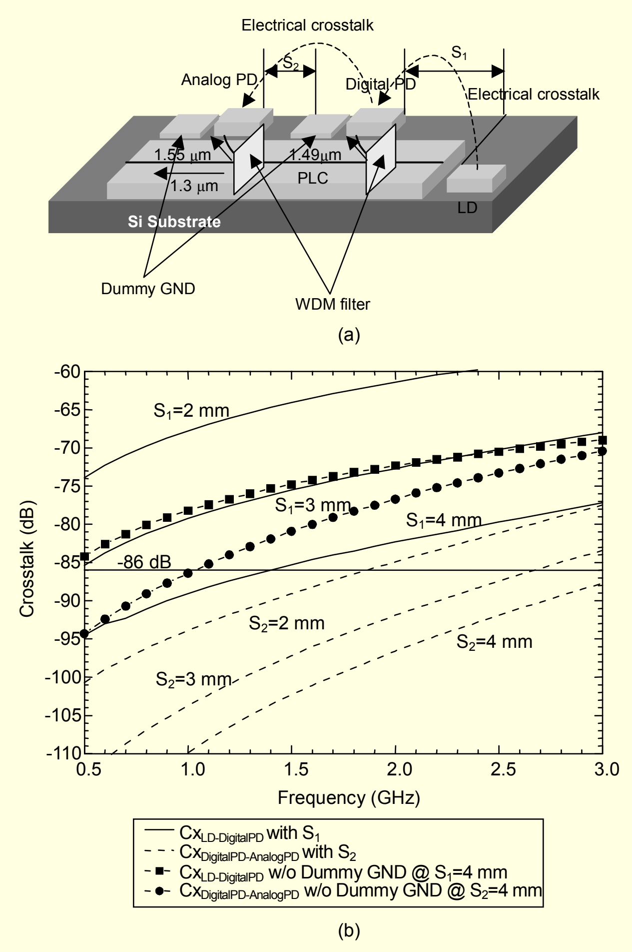

Fig. 5. (a) Electrical crosstalk analysis model for the finite element method and (b) analysis results.

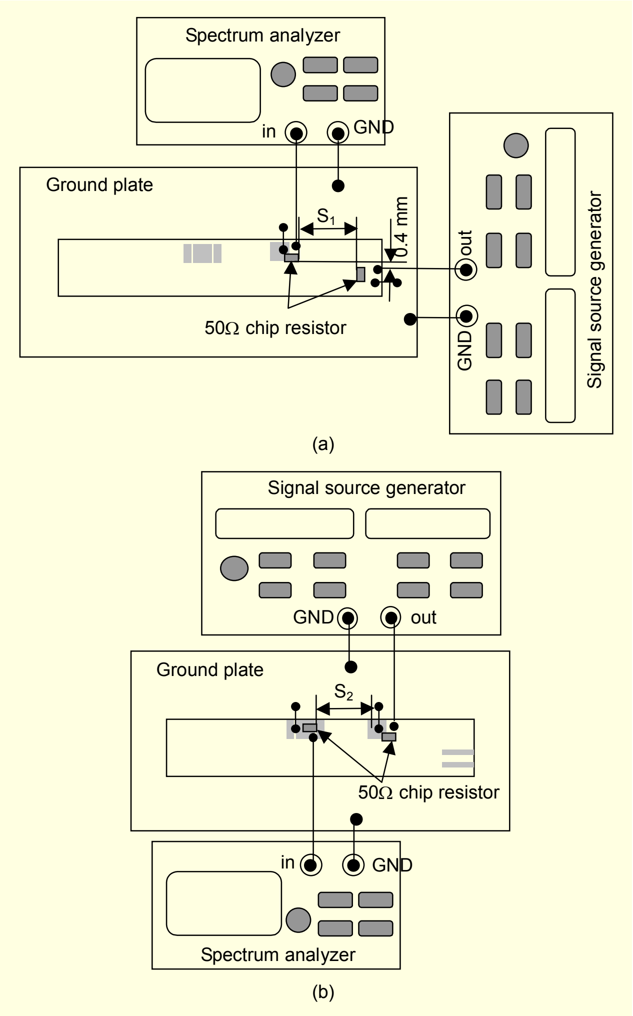

Fig. 6. Experimental setup for measuring the electrical crosstalk between (a) the LD and D-PD and (b) the D-PD and A-PD.

ground structure at $S_1 = S_2 = 4$ mm. And $Cx_{LD\text{-}DigitalPD}$ and $Cx_{DigitalPD\text{-}AnalogPD}$ are suppressed as 10 and 20 dB in comparison with a conventional structure, respectively. Accordingly, the dummy ground line in the 1.25 Gbps optical triplexer module can be implemented easily and is an effective method for reducing the electrical crosstalk phenomena.

III. Measurement and Implementation

Figure 6 shows the experimental systems for measuring the electrical crosstalk characteristics of 1.25 Gbps optical triplexer modules. Figure 6(a) shows the measurement system to verify the electrical crosstalk characteristics between the LD and D-PD, and Fig. 6(b) shows the measurement system to verify the electrical crosstalk characteristics between the D-PD and A-PD. In this figure, the experimental system is composed of a signal source generator, spectrum analyzer, and the 1 mm thickness Si substrate with the dummy ground and 50 Ω termination resistor on a ground plate. We have measured the electrical crosstalk characteristics in the case of the dummy ground structure, which used a 50 Ω termination resistor. Then, to verify electrical crosstalk of under –86 dB, we should use the spectrum analyzer that has a noise floor of less than –100 dBm and a dynamic range of more than 100 dB. Also, we have used a sweep signal source generator that induces electric fields into the signal line and Si substrate. The bottom of the Si substrate should be connected with the ground plate, as should the spectrum analyzer and sweep signal source generator ground.

The experimental results of the electrical crosstalk between the LD and D-PD, and between the D-PD and A-PD, are shown in Figs. 7 and 8 with simulation results, respectively. As shown in Figs. 7(a) and 8(a), the simulation results show a good agreement with the experimental results. In these figures, S_1, g_1, S_2, and g_2 are the distances between the LD and D-PD, D-PD signal line and dummy ground line, D-PD and A-PD, and A-PD signal line and dummy ground line, respectively.

In the case of $g_1 = g_2 = 100$ μm, Figs. 7(a) and 7(b) show the

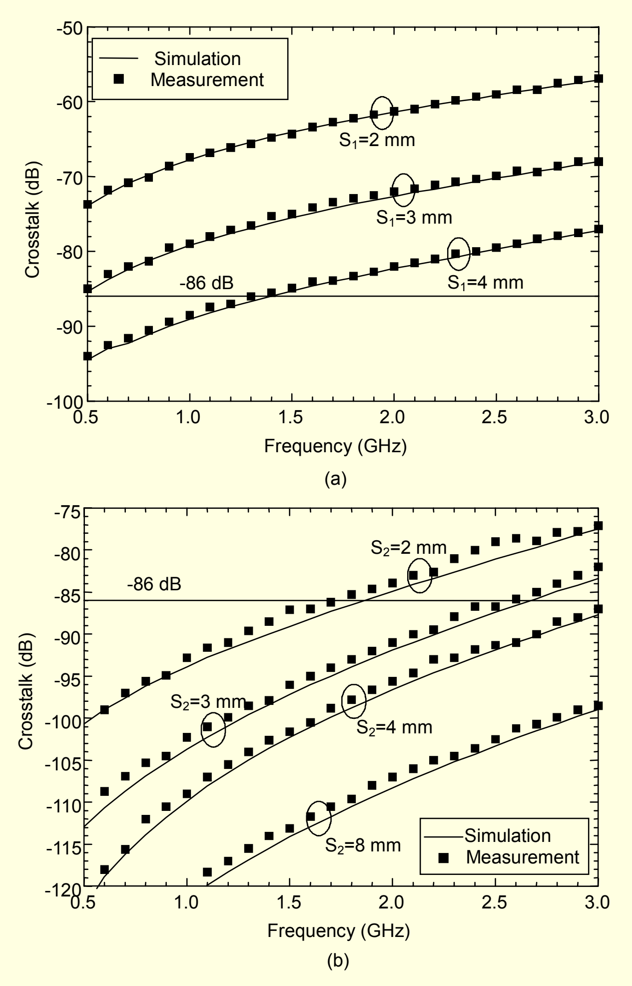

Fig. 7. Electrical crosstalk measurement results (a) between the LD and D-PD with the distance (S_1) and (b) between the D-PD and A-PD with distance (S_2).

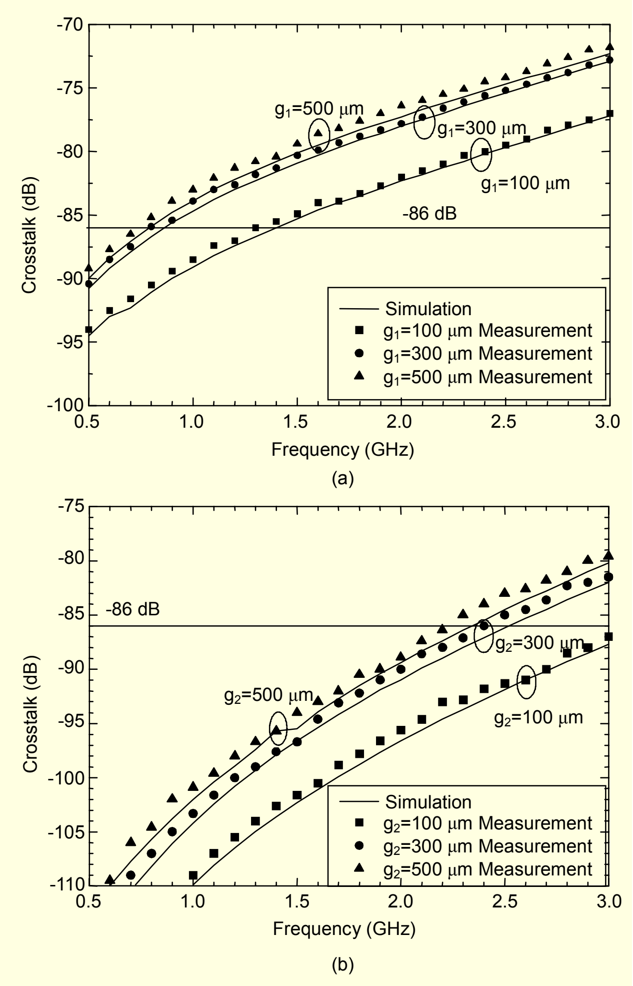

Fig. 8. Electrical crosstalk measurement results (a) between the LD and D-PD with gap (g_1) and (b) between the D-PD and A-PD with gap (g_2).

electrical crosstalk as parameters of the distances, S_1 and S_2. From these figures, the electrical crosstalk increases by decreasing the distance due to the increase of the fringing electric field. From Fig. 7(a), in the viewpoint of the stability of digital receiver operation, a crosstalk level of about at least -86 dB between the LD and D-PD in the frequency rage of 0 GHz to 1.25 GHz is necessary. Therefore, the LD/D-PD distance (S_1) has to be kept to more than 4 mm. Also, from Fig. 7(b), for the crosstalk characteristics to satisfy the stability of the analog receiver operation, a crosstalk level of about at least -86 dB between the D-PD and A-PD within the frequency range of 0 GHz to 3 GHz is necessary. Then, the D-PD/A-PD distance (S_2) has to be kept to more than 4 mm. Accordingly, we can confirm that the dummy ground lines that are installed more closely to the signal line than the bottom ground of the Si substrate limit the fringing electric field through the Si substrate.

Also, the crosstalk characteristics with the distance between signal line and dummy ground line are shown in Figs. 8(a) and 8(b). In Fig. 5, because the dummy ground structure is similar to an asymmetric coplanar strip (CPS) structure, the characteristic impedances of this asymmetric CPS has increased by increasing the distance between the signal line and dummy ground line [5].

In the case of $g_1 = g_2 = 300$ μm and 500 μm, the crosstalk characteristics are measured in the electrical crosstalk through the resistive Si substrate and in the scattering of the electric field by impedance mismatch. The impedance mismatch is caused by the impedance difference between the spectrum analyzer input port with 50 Ω characteristics impedance and asymmetric CPS lines with higher than 50 Ω characteristics impedance. Therefore, in the case of $g_1 = g_2 = 300$ μm and 500 μm, we can observe worse crosstalk characteristics than in the case of $g_1 = 100$ μm.

Accordingly, from Figs. 8(a) and 8(b), the electrical crosstalk is increased by increasing g_1 and g_2 due to an impedance mismatch between the asymmetric CPS and spectrum analyzer input port. We have found that the electrical crosstalk characteristics for satisfying the stability of digital and analog receivers are obtained by selecting $g_1 = g_2 = 100$ μm.

Consequently, from simulation and measurement results, to satisfy the sensitivity of digital and analog receivers, the distance between the LD and D-PD, and the distance between D-PD and A-PD, have to be more than 4 mm, respectively. A dummy ground line with a 100 μm gap from the D-PD and A-PD signal line is established for satisfying the crosstalk characteristics. These results show the validity of the proposed dummy ground line structure and the low electrical crosstalk optical modules. Thus, in the case of a 1 mm thick Si substrate, it can be concluded that the 1.25 Gbps optical triplexer module for EPONs can be obtained by selecting the LD/D-PD and D-PD/A-PD distances at about 4 mm, with the dummy ground line at a 100 μm gap away from the D-PD and A-PD signal line.

IV. Conclusion

The IEEE802.3ah standards specify the data rate and digital receiver sensitivity of a gigabit optical transceiver module to be 1.25 Gbps and –24 dBm @ 10^{-12} BER, respectively [2]. The ITU-T 983.3 [9] and Telecommunication Technology Association Standard in Korea KO-07.0020 [10] standards specify the analogue receiver sensitivity to be a –7.7 dBm @44 dB SNR. Accordingly, the electrical crosstalk between the LD and D-PD has to less than –86 dB within the frequency range of 0 to 1.25 GHz to satisfy the sensitivity of the IEEE 802.3ah standard. Also, the electrical crosstalk between the D-PD and A-PD has to be less than –86 dB within the frequency range of 0 to 3 GHz to satisfy the sensitivity of the ITU-T G.983.3 and TTA standards. Therefore, the electrical crosstalk characteristics between optoelectronic devices on a PLC platform become as important as large-scale-integration systems because a LD/D-PD/A-PD full-triplex operation is necessary in a gigabit PON system. There has been no report for the crosstalk characteristics of a 1.25 Gbps optical triplexer module with a PLC platform on a lossy Si substrate. We have attempted the characterization of crosstalk effects on a 1.25 Gbps optical triplexer module with a PLC platform on a lossy Si substrate.

Consequently, we have analyzed the electrical crosstalk phenomena and proposed a Si substrate structure with a dummy ground line that is the simplest low-crosstalk layout configuration in a 1.25 Gbps optical triplexer module. We have designed the 1.25 Gbps optical triplexer module on the proposed Si substrate structure using a three-dimensional-structure simulator that utilizes the finite element method. From our measurements, we have found that the electrical crosstalk between the LD and D-PD in the triplex gigabit optical transceiver is less than –86 dB in the frequency range of 0 to 1.25 GHz. The electrical crosstalk between the D-PD and A-PD should be less than –86 dB in the frequency range of 0 to 3 GHz. Also, we have inserted the dummy ground line beside the D-PD signal line and A-PD signal line in order to decrease the electrical crosstalk. Therefore, the proposed Si substrate structure, which contains the dummy ground line with 100 μm space from the signal lines and separations of 4 mm among devices, satisfies an electrical crosstalk level comparable to a simple structure. This proposed structure can be easily implemented with design convenience and greatly reduces the Si substrate size by about 50 %.

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