Optical Harmonic Modulation-Demodulation Techniques for High-Speed Light wave Transmission

Young-Kyu Choi *Member, KIMICS*

***Abstract*—**High-speed harmonic optical modulation-demodulation schemes are presented and a possibility of the schemes for applying to high-speed light wave transmission system is tested at microwave frequency range. An example of this concept is as follows : Light wave is modulated succeedingly through cascaded optical modulators by a sub-carrier to produce a modulated light wave at harmonic frequency which is higher than the feasible frequency of the individual modulators. For demodulation of the base-band signal, the high frequency optical sub-carrier is down-converted by the same kind of optical modulator with the same concept of harmonic modulation.

***Index Terms*—** Light wave transmission , Harmonic modulation, Frequency conversion .

I. INTRODUCTION

In the light wave communication system, the 10-Gb/s systems are now widely used and the deployment of 40-Gb/s systems is expected to start soon [1-5]. Progress in techniques of electronic device fabrication and optoelectronic components has enabled research in 80-Gb/s up to 107-Gb/s electronic time-division multiplexing system (EDTM) [6-8]. For data modulation in high-speed ETDM systems, only external optical MZ modulators are applicable. Recently, the research effort on InP-based MZ modulators has been increased. Their application in 40-GB/s operation has been reported with low required driving voltages of 2×1.3 V. In [9], dual-drive MZ modulators were used, and an 80-Gb/s signal was generated with a matched pair of modulator driver amplifiers. In [10], a 107-Gb/s transmitter was demonstrated.

For ultrahigh bit rate ETDM systems, in contrast, the receiver usually comprises a high-power photodiode an electronic de-multiplexer, and electronic clock recovery [11-13]. In the literature, even the detection of a 160-Gb/s optical time-division multiplexing (OTDM) signal was demonstrated by applying a waveguide photodiode having a 3-dB bandwidth of 100 GHz and a responsivity of 0.5 A/W was reported [14]. Recently, a waveguide photodiode with 3-dB bandwidth of 120 GHz and a responsivity of 0.5 A/W was reported [15].

Manuscript received March 2, 2008; revised May 13, 2008. Corresponding Author : Young-Kyu Choi
Authors are with the Department of Electronics Engineering, Silla University, Busan, 617-736, Korea (Email: ykchoi@silla.ac.kr)

However, an extensive bandwidth of a light wave is still remained unused, mainly because there are limitations that the optoelectronic components can not exceed a certain speed. As an alternative way to overcome these limitations and extend the available frequency range of a light wave, we have proposed high speed optical modulation and demodulation techniques such as cascade modulation, square modulation [16], and frequency conversion demodulation [17]. As an example, a light wave can be modulated in reverse polarity by a subcarrier frequency, if two optical modulators are cascaded-connected and excited in reverse polarity by a subcarrier. In another way, if an optical modulator with a square characteristic is used, the light wave is also modulated at twice the modulation frequency.

Though the detectable frequency of a photodiode is lower than that of optical modulators in general, the subcarrier frequency higher than it can be converted into a lower frequency by use of an optical modulator excited at a local frequency inserted in front of a detector, so that the signal included in the subcarrier can be extracted.

These facts may signify a possibility that the frequency range lying beyond the feasible frequency of conventional modulators and demodulators may be utilized as another channel of signal transmission besides the baseband channel used so far. The main advantage of these techniques are in that, while the readily available optoelectronic components are still used, super high-capacity light wave transmission system can be composed with a single wideband optical fiber.

In this paper, after reviewing briefly the basic theory of the above modulation and demodulation, we describe a method how the bandwidth of an optical communication system is made wide by an appropriate use of such characteristics of optical modulation and demodulation, in combination with the technique of frequency multiplexing.

II. HARMONIC MODULATION THEORY

2.1 Two-stage cascade modulation

Light wave modulation at frequency ω(ω is angular frequency of a sub-carrier) is expressed by

$$P = P_0\{1 - m - m\cos(\omega t + \theta)\} \qquad (1)$$

Nothing that in usual optical modulators the instantaneous peak power of the modulated light wave cannot exceed the average input optical power P_0. Since the magnitude of the light wave should be positive, the modulation index, m must be satisfied $|m \leq 1/2|$ ($m = 1/2$ means 100% modulation). If the modulated light wave is modulated again in inverse-phase with the same type of modulator, we obtain

$$P = P_o\left\{1 - 2m + \frac{m^2}{2} - \frac{m^2}{2}cos2(\omega t + \theta)\right\} \quad (2)$$

This tells that the light wave is modulated at twice the fundamental frequency ω with the fundamental frequency ω being canceled. If we set the modulation index of each modulator to be 100%, that of 2ω frequency component also becomes 100%.

2.2 The n-stage cascaded modulation

The above mentioned modulation technique can be extended to an arbitrary number of cascade connected modulators. If we connect the n modulators in cascade, the modulated light wave is expressed as

$$P = P_o \prod_{k=1}^{n}\left\{1 - m - m\cos\left(\omega t - \frac{2k\pi}{n}\right)\right\} \quad (3)$$

where the phases of each modulators were shifted by the same value to achieve the total phase shift 360°. Since the n-th root of 1 is $exp\ (j2k\pi/n)$, we can write as

$$x^n - 1 = \prod_{k=1}^{n}\left\{x - \exp\left(\frac{j2k\pi}{n}\right)\right\} \quad (4)$$

Substituting $x = exp\ (\alpha + j\omega t)$ into Eq. (4), and taking the square of its absolute value and dividing it by $2\ exp\ (n\alpha)$ we obtain

$$cosh(n\alpha) - cos(n\omega t) = 2^{n-1}\prod_{k=1}^{n}\left\{cosh\alpha - cos\left(\omega t - \frac{2k\pi}{n}\right)\right\} \quad (5)$$

If we set

$$cosh\alpha = (1 - m)/m \quad (6)$$

we have

$$exp(\pm\alpha) = \left\{1 - \mathrm{m} \pm (1 - 2\mathrm{m})^{1/2}\right\}/\mathrm{m} \quad (7)$$

With the aid of the relations above, Eq. (3) is calculated to be

$$P = P_o \cdot A\{1 - M\ cos(n\omega t)\} \quad (8)$$

Where

$$A = \frac{\{1 - m + (1 - 2m)^{1/2}\}^n + \{1 - m - (1 - 2m)^{1/2}\}^n}{2^n}$$

$$M = \frac{2m^n}{\{1 - m + (1 - 2m)^{1/2}\}^n + \{1 - m - (1 - 2m)^{1/2}\}^n}$$

That is to say, if we connect the n modulators in cascade, n-th order harmonic modulation is achieved with the fundamental and any other harmonic frequencies being canceled. If the modulation index of each modulators 100% ($m = 1/2$), that of n-th order harmonic modulation also becomes 100%. In the case of passive optical modulators, the magnitude of the optical power decreases to $P/2^{2n-1}$. However, if modulation index m of each modulators is small, the modulation index of the n-th order harmonic modulation decreases to about $2(m/2)^2$ without the optical power decreasing. So, the modulation index should be determined according to the type of application.

2.3 Square modulation

If a modulation having a square characteristic is used, modulation at twice the sub-carrier frequency is obtained with a single optical modulator according to the trigonometric formula,

$$P = P_o cos^2(\omega t + \theta) = P_o\{1 + cos\ (2\omega t + 2\theta)\}/2 \quad (9)$$

Needless to say, higher harmonic modulation is also possible by cascading a plural number of this type of optical modulator, following the same principle as described above.

III. EXPERIMENTAL RESULTS

3.1 Device fabrication and characteristics

A two stage cascaded interferometric optical modulator was fabricated by Ti diffusion on z-cut y-propagating $LiNbO_3$ substrate. The design structure and parameters of the waveguide are shown in Fig.1. The parameters were chosen for a He-Ne laser as a light source.

A Ti-film of 30 nm thick was evaporated onto the $LiNbO_3$ substrate. The Ti was patterned using photolithograph and chemical wet etching. The Ti was diffused into the substrate at 1020℃ for 5 hours with O_2 flowing over Ti which had been passed through pure water in order to reduce surface waveguiding. A 150 nm buffer layer of SiO_2 was supported onto the substrate.

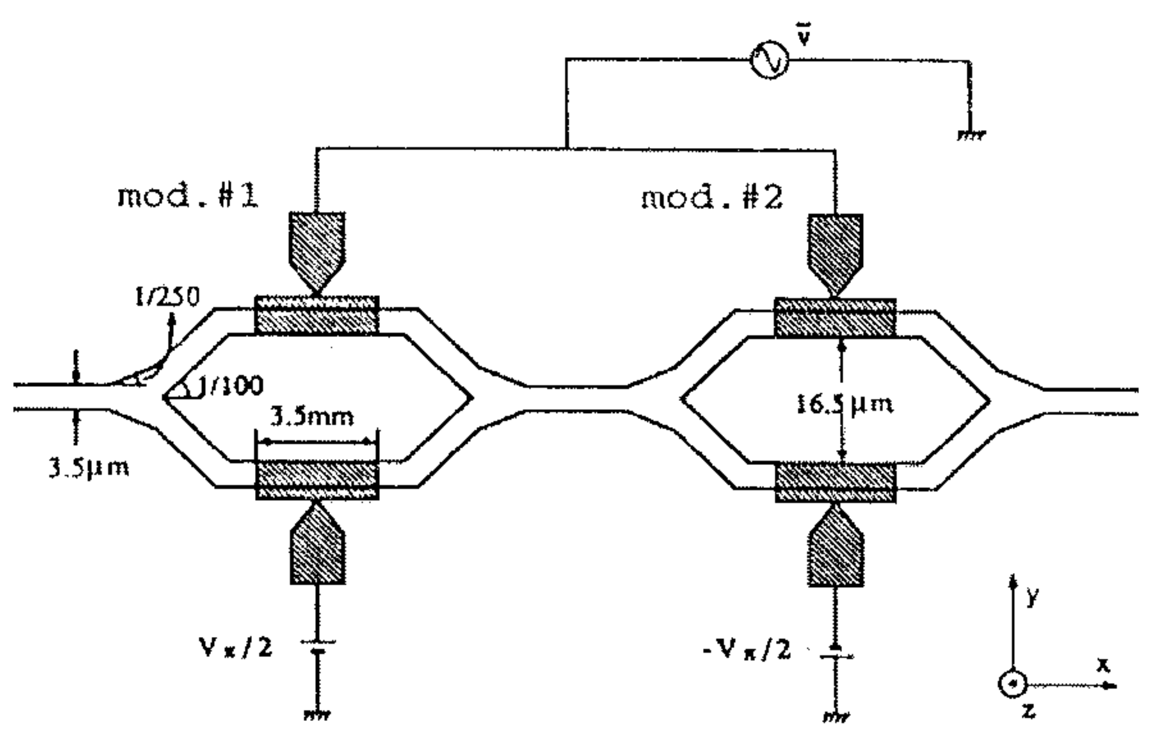


Fig. 1 Design structure and parameters of the waveguide

The electrodes were deposited by evaporating Al of 200 nm thick onto the buffer layer and patterning it using photolithograph and chemical wet etching. The electrode lengths were to be 3.5mm, the gap 16.5 μm and the width 15 μm. The substrate edges were optically polished to inject light wave efficiently from a light source. Under this condition we expect that only the dominant mode may be guided. The loss of the Y-branch is expected to be less then 1dB [18]. The half-wave voltage of each modulator of this structure was estimated to be 14V from the half-wave voltage formula [7] with the reduction factor for the applied electric field $\Gamma \cong 0.3$. The measured DC characteristic was shown in Fig.2. About 14 V voltage swing switches the device between its on and off states. This is good agreement with the estimated results.

To make a high-efficiency and wide-band optical modulator, traveling-wave type electrodes of long length is desirable. However, we did not lay much stress on bandwidth and half-wave voltage in fabricating the electrodes of the modulator, because of our major interest of this experiment is to confirm the principle of the above-mentioned modulation theory.

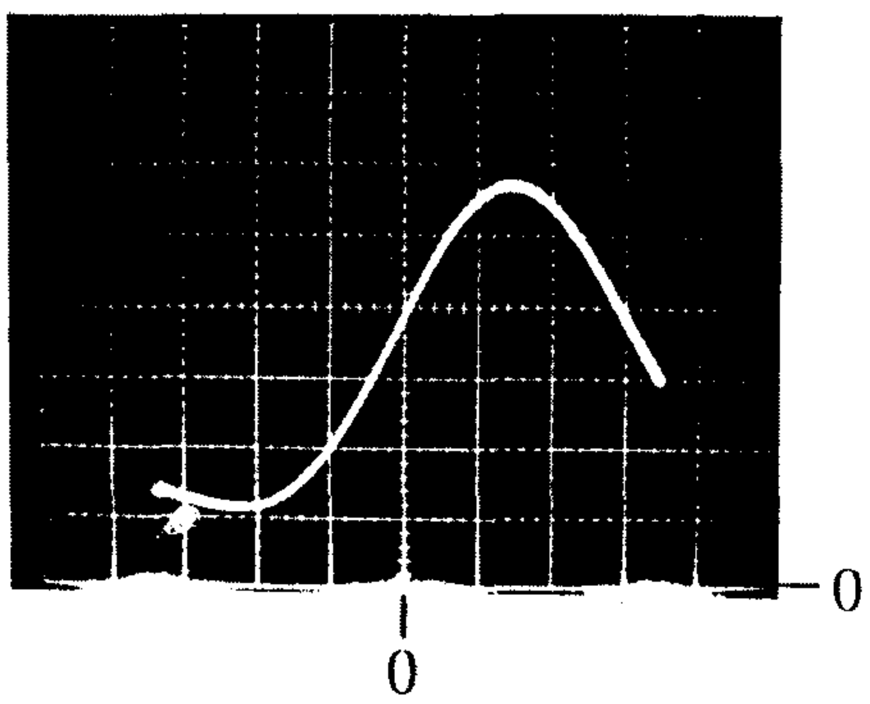
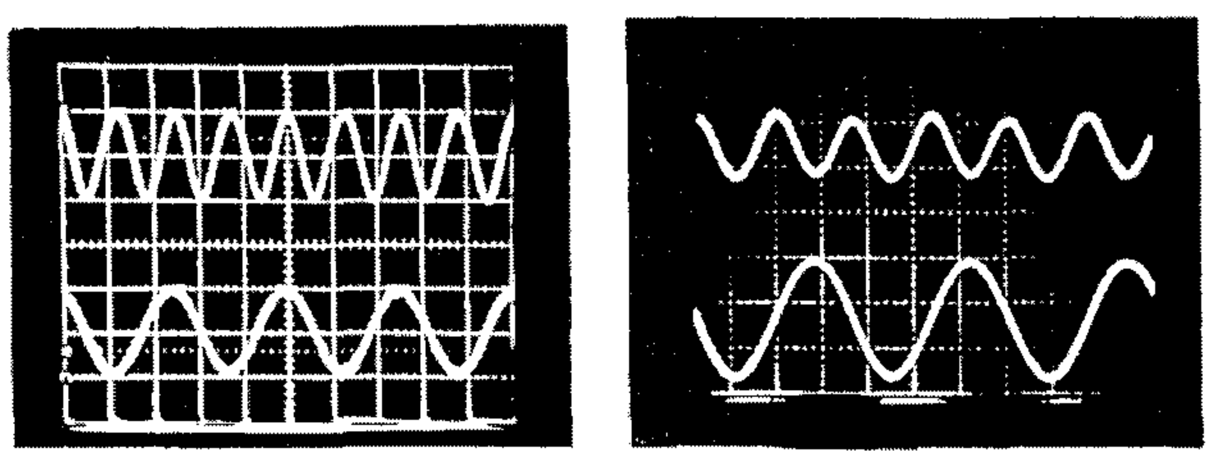


Fig. 2 Observed output characteristic of the modulator

3.2 Harmonic modulation experiment

We carried out the square modulation experiment using only the front-end modulator. The characteristic of the modulator is sinusoidal variation with respect to bias voltage. If a bias point is chosen in the region of the square characteristic curve, twice the fundamental frequency is obtained. The bias was chosen in the characteristic curve of Fig. 2, near 0V or 15V.



Top:Output(40MHz)
Bottom:Input(20MHz)
(a) Square modulation

Top:Input(40MHz)
Bottom:Output(20MHz)
(b) Cascade modulation

Fig.3 Waveform of the harmonic modulation experiment

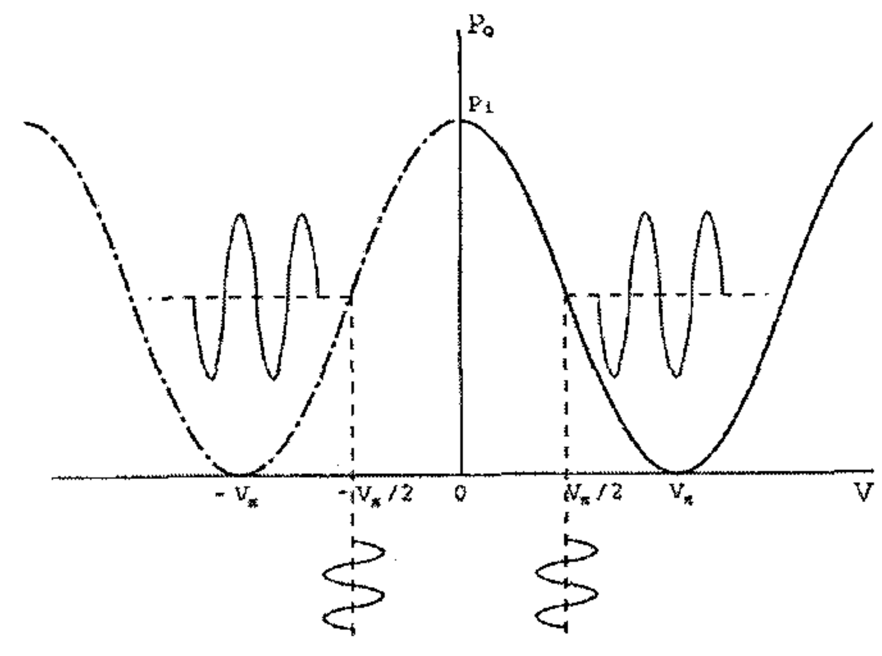


Fig. 4 Bias points of the two-stage cascaded modulation

The 20 MHz modulation signal was applied and the light output modulated by 40 MHz signal was observed as shown in Fig. 3(a). On the other hand, in the case of cascaded modulation, the characteristic of one of the interferometric modulators is expressed by

$$P = \frac{1}{2}P_o\left\{1 + cos\left(\pi\frac{v}{V_\pi}\right)\right\} \tag{10}$$

If the bias voltages of each modulator are chosen at $v = \pm V_\pi/2$ as shown in Fig. 4, phase difference of π is produced between the two modulators. So, we set the modulation voltages to be $v = \bar{v} \pm V_\pi/2$ with $\bar{v} = Vcos(\omega t + \theta)$. Proving that the interferometric optical modulators operate ideally, the light output amplitude may be calculated as

$$\begin{aligned} P(\bar{v})/P_o &= \frac{1}{4}\left\{1 + cos\left(\pi\frac{\bar{v}}{V_\pi} + \frac{\pi}{2}\right)\right\}\left\{1 + cos\left(\pi\frac{\bar{v}}{V_\pi} + \frac{\pi}{2}\right)\right\} \\ &= \frac{1}{8}\left[2 - \left(\pi\frac{V}{V_\pi}\right)^2\{1 + 2(\omega t + \theta)\}\right] \end{aligned} \tag{11}$$

where we have assumed for simplicity that $|V|V_\pi| \ll 1$. The modulation frequency has been doubled with fundamental frequency being canceled. In the experiment, we selected the bias of the two modulators to be $V_\pi/2 = 7$V for mod.#1 and $-V_\pi/2 = -7$V for mod.#2, so that we may obtain reverse-phase cascaded modulation. Since the modulation characteristics of the two modulators were slightly different from each other, we had adjust the modulation indices of the two modulators to cancel the fundamental frequency completely. Consequently, doubled frequency of 40 MHz for the applied modulation signal frequency of 20 MHz was observed as shown in Fig. 3(b) similar to the square modulation experiment.

IV. FREQUENCY CONVERSION DEMODULATION

The response frequency of optical demodulators is generally lower than of optical modulator, so that the modulated signal provided by the above methods cannot be detected by the normal mode of optical detection. So, we employed a technique to demodulate the signal by down-converting the sub-carrier frequency. Moreover, when the modulation frequency of light wave is high, it is often more convenient to perform the signal processing after the frequency is converted to a lower frequency instead of direct treatment of the detected signal. The electrically down-converting technique using the nonlinearity of the photodiode such as a p-i-n PD or an APD had been reported by Kulzcyk et al [19]. However, the detection technique is inefficient beyond the cutoff frequency of a photo-detector.

If the high frequency sub-carrier signal is down-converted optically by an optical modulator before direct detection, we can achieve the same results as electrically down-conversion technique. Let us consider the case that an interferometric modulator is expressed by Eq.(10). We set the local signal voltage $v = Vcos(\omega_l/2)t$ in Eq.(10), and use a standard algebraic expansion, we have

$$P = \frac{1}{2}P_o\left\{1 + J_o\left(\pi\frac{V}{V_\pi}\right) + 2\sum_{n=1}^{\infty} J_{2n}\left(\pi\frac{V}{V_\pi}\right)cos2n\omega_l t\right\} \quad (12)$$

when an intensity modulated light wave at frequency ω_m enter into the modulator, the output signal will be given by

$$P = \frac{1}{2}P_o\left\{1 + J_o\left(\pi\frac{V}{V_\pi}\right) + 2\sum_{n=1}^{\infty} J_{2n}\left(\pi\frac{V}{V_\pi}\right)cosn\omega_l t\right\}$$
$$+\frac{1}{2}P_oJ_o\left(\pi\frac{V}{V_\pi}\right)cosn(\omega_m t + \theta) + \frac{1}{2}P_o\sum_{n=1}^{\infty} J_{2n}\left(\pi\frac{V}{V_\pi}\right)$$
$$\cdot\,[cos\{(n\omega_l + \omega_m)t + \theta\} + cos\{(n\omega_l - \omega_m)t + \theta\}] \quad (13)$$

The term of interest is that containing $\omega_l - \omega_m$. When the modulation fequency ω_m is higher than the cut-off frequency of the photo-detector $\omega_l - \omega_m \ll \omega_c$, the down-converted optical signal at $\omega_-(= \omega_l - \omega_m)$ is obtainable. The angle-modulated base-band signal $\theta(t)$ can be demodulated by a discriminator without distortion in this process.

V. SYSTEM EXPERIMENTS

5.1 Cascade modulation and direct detection system

As an example the two-stage cascaded modulator which was fabricated in section 3 was utilized. Due to the availability of experimental apparatus it was necessary to carry out the experiments at lower frequency.

Experimental set-up was shown in Fig. 5. The sub-carrier of 20 MHz was FM-modulated by a base-band of 20 kHz. The FM-modulated sub-carrier signal was divided into two by a directional coupler and fed to each modulator biased in reverse-phase to each other. The applied signal to each modulator was shown in Fig.6. In order to trace the signal flow the change of waveform in each stage was observed. Fig. 6(b) shows the signal detected by the APD. The upper trace is the applied signal of 20 MHz, and the bottom trace is the doubled signal of 40 MHz. As is to be expected, even though the modulation index was decreased the doubled frequency was obtained. In order to obtain the original signal, the doubled sub-carrier signal of 40 MHz detected by the APD was demodulated by the FM-detector.

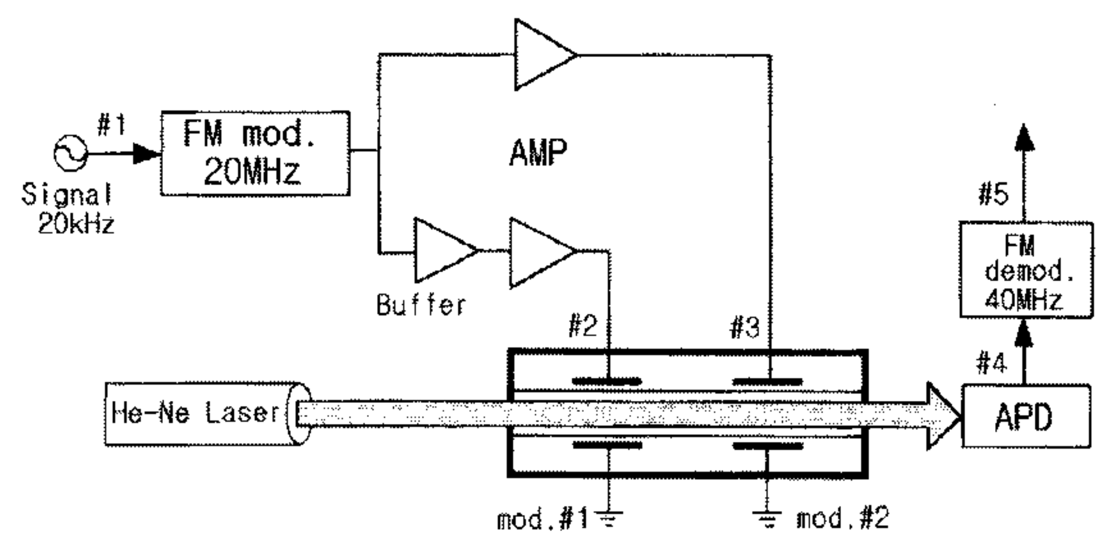


Fig. 5 Experimental set-up of cascade modulation system

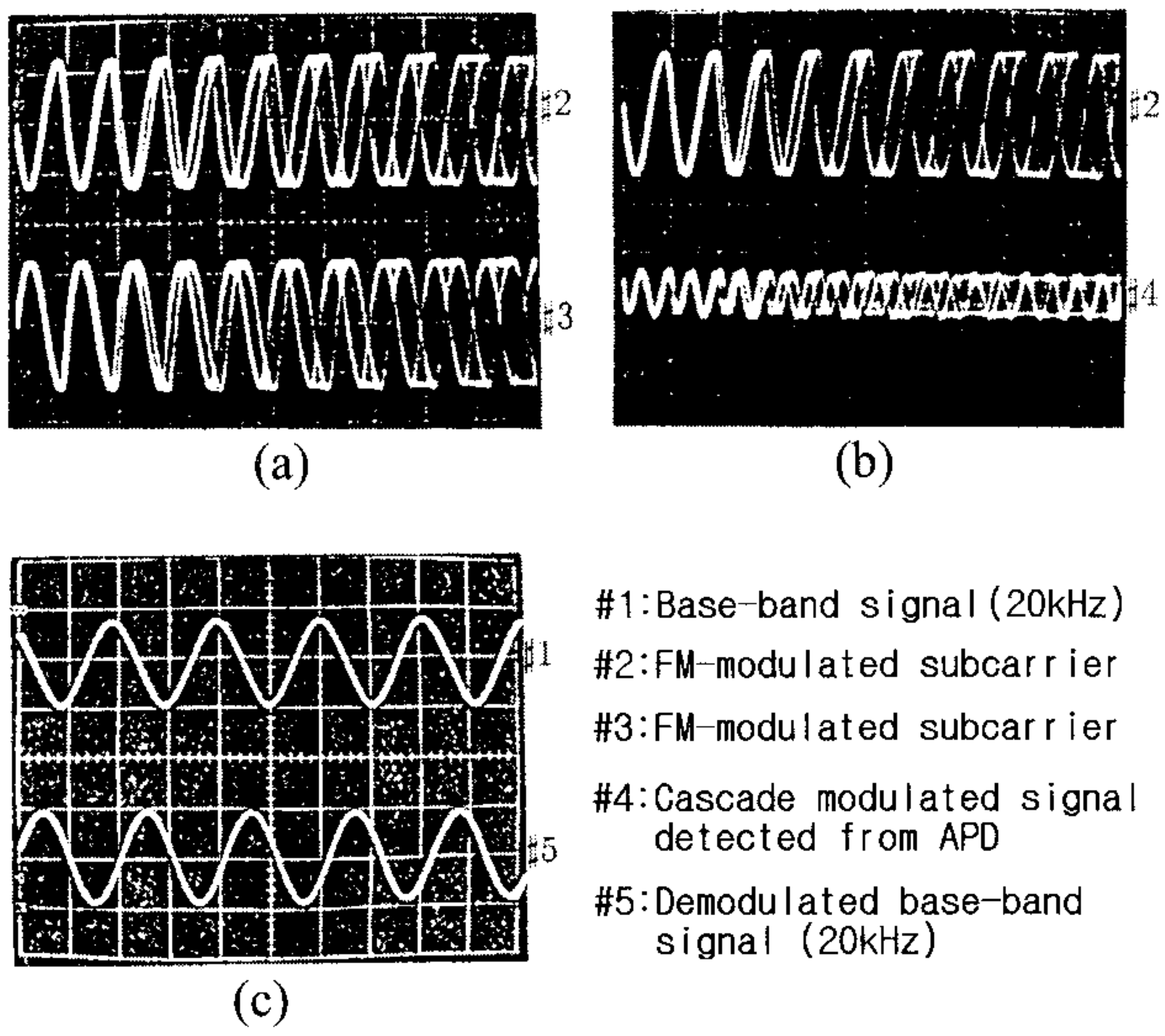


Fig. 6 Waveform of each stage

The output of FM-detector is shown in Fig. 6(c). The upper trace is original signal and the bottom trace is the detected signal of 20 kHz. The original signal was obtained without distortion.

5.2 Square modulation and optical down-conversion system

A schematic diagram of square modulation and optical down-conversion system is shown in Fig. 7. In this model experiment the two stage cascade modulator was also utilized. Only the front end modulator was driven to acquire the square wave characteristic. The rear-end modulator was used to apply a local signal in order to down-convert the doubled sub-carrier signal. The down-converted signal was detected by an APD. The sub-carrier of 100 MHz was FM-modulated with a base-band signal of 20 kHz.

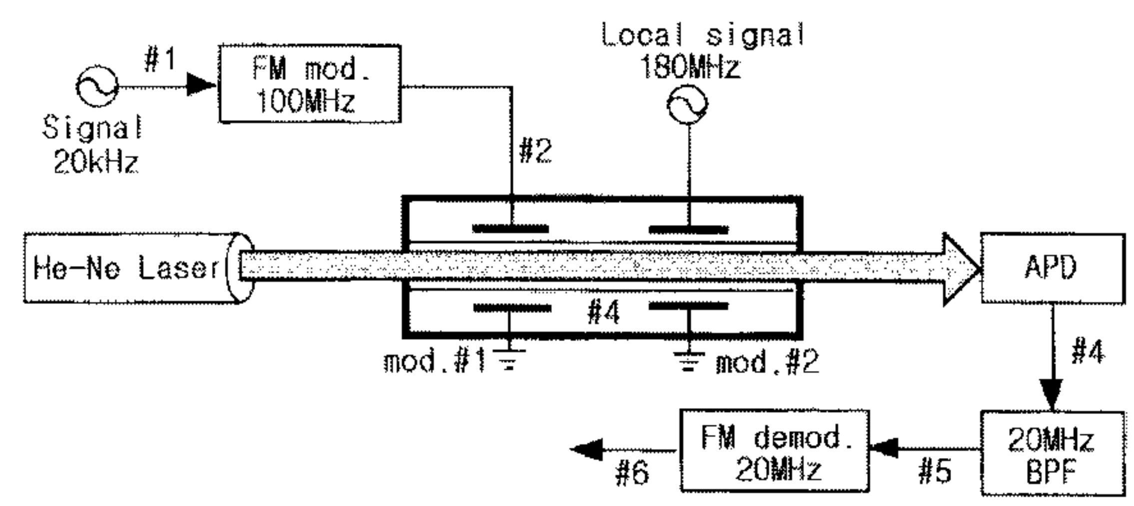


Fig. 7 Experimental set-up of square modulation system

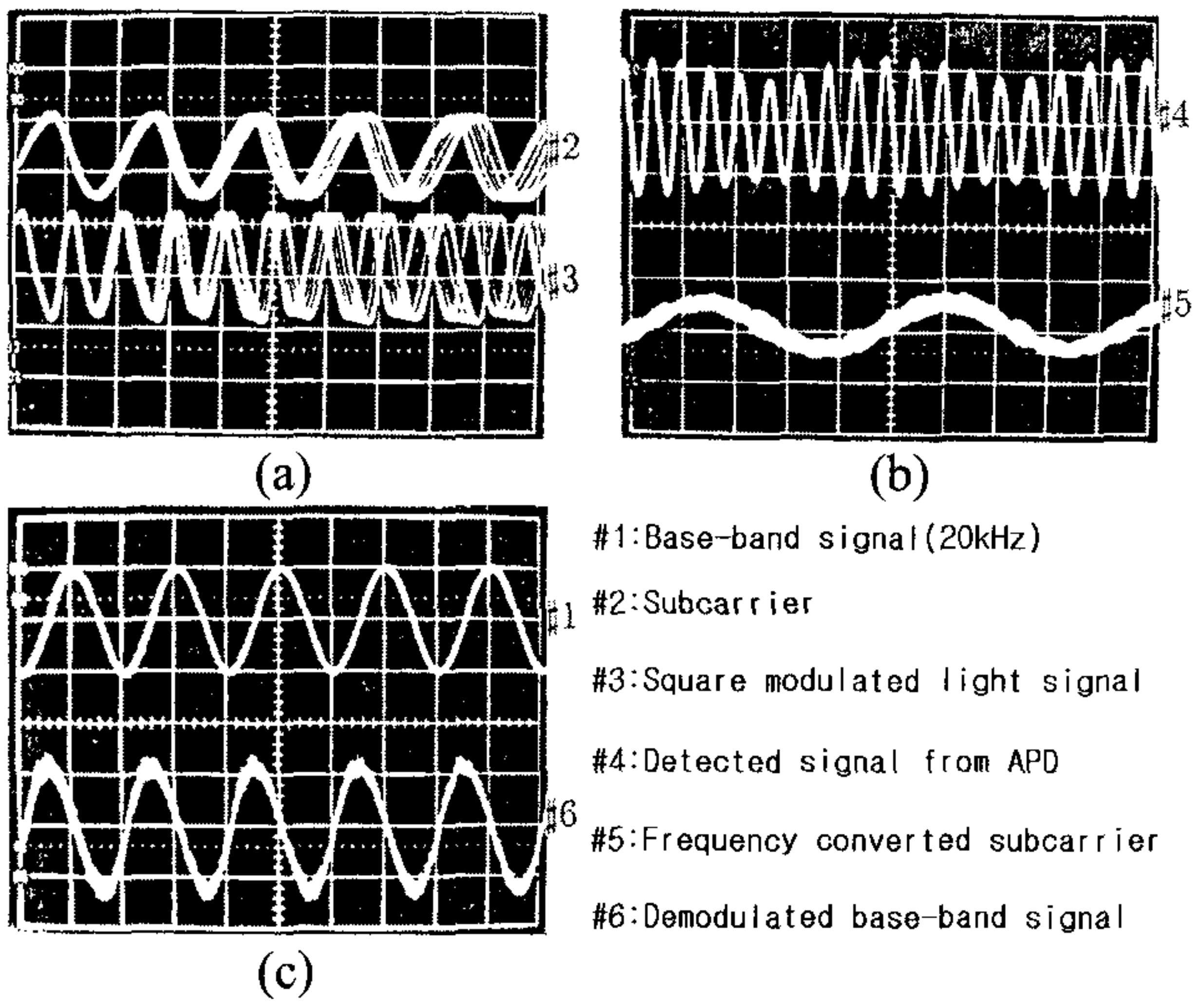


Fig. 8 Waveform of each stage

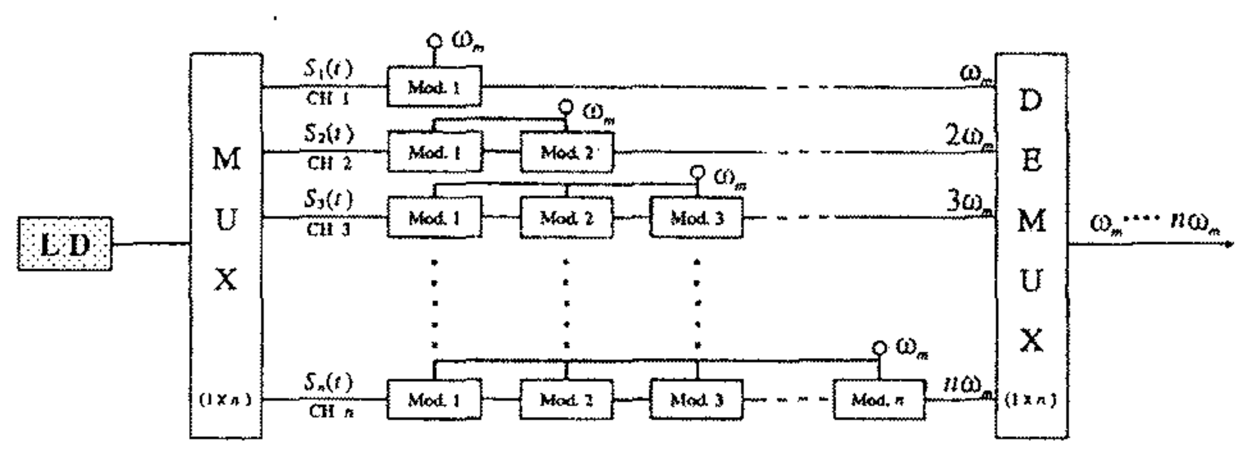
The FM-modulated sub-carrier was fed to the fore-end electrodes so that the light wave from the He-Ne laser was modulated at twice the sub-carrier frequency. Before the doubled sub-carrier signal was detected with an APD, it is modulated once again at the local signal frequency of 180 MHz. The down-converted sub-carrier signal of 20 MHz is detected directly by an APD along with the dominant signal. The output of the APD was fed to a 20 MHz band-base filter to select the down-converted sub-carrier signal of 20 MHz.

Finally, the FM-demodulator was used to demodulate the base-band signal. We observed the change in the waveform at each stage from the base-band signal to the final demodulation signal. The FM-modulated sub-carrier signal of 100 MHz and the square modulated sub-carrier signal of 200 MHz are shown in Fig. 8 (a). As shown in Fig.3 (a), a doubled sub-carrier signal of 200 MHz was observed. Fig.8 (c) shows the finally demodulated signal compared with the original signal. The result shows that this type of light wave transmission system also can transmit signals without distortion.

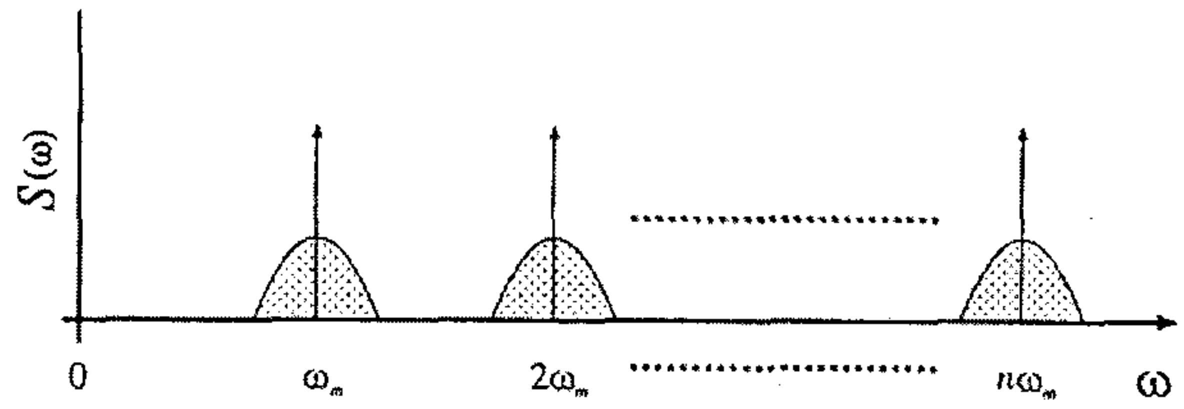
V. DICUSSIONS

High-speed harmonic light wave modulation does not necessary mean wide-band transmission. Even though it is possible to generate an ultrafast light wave CW, it does not follow simply that the transmission of high-capacity information using the ultrafast light wave CW is possible. The cascaded or square modulation technique, while utilizing conventional relatively low-speed optical modulator, can generate an ultrafast light wave CW. Furthermore, by means of integration of many modulators in a single substrate, it has an advantage to minimize the light input/output loss. We will show how the harmonic modulation-demodulation techniques are used to construct a ultra-high-capacity light wave transmission system.

When an optical modulator is used in a ultra-high-capacity transmission system, the optical modulator need not cover wide-bandwidth. Even in the case that the optical modulator has narrow-bandwidth, if high-speed harmonic light wave modulation is possible, ultra-high-capacity information can be transmitted through s single optical fiber in the long haul point to point system. As an example, we showed the cascade modulation system to increase the transmission capacity in Fig. 9(a).



(a) Multiplexed signal of cascaded modulation



(b) Frequency spectrum

Fig. 9 An example of harmonic modulation system

The output from the light source is multiplexed by the $1 \times n$ multiplier. At channel 1(CH1), Mod.1 is modulated at the sub-carrier $\omega_m$which is modulated by the base-band signal $S_1(t)$. At channel 2(CH2), Mod.1 is modulated at the sub-carrier ω_m which is modulated by the base-band signal $S_2(t)$, and the output of Mod.1 is modulated succeedingly again by the sub-carrier ω_m in Mod.2. The signal $S_2(t)$, moves to twice the frequency of $2\omega_m$. The next stage channels are also modulated with the same modulation technique. The output of each channel is demodulated by the $n \times 1$ dultiplexer and transmitted through a single optical fiber. The spectrum of light wave transmitted through the optical fiber is shown in Fig. 9(b). Utilizing the high frequency region of the light wave which has left unused, we can transmit very high capacity information through a single optical fiber.

VI. CONCLUSIONS

We have proposed a new-type of harmonic optical modulation-demodulation technique in order to make use of the high frequency range of light wave which is left unused. A two-stage cascaded optical modulator was fabricated in order to confirm our proposal.

Two types of model system experiments were carried out at lower frequency. The FM-modulated sub-carrier of 20MHz was modulated again by the cascade modulation, and the applied sub-carrier signal of 40MHz was demodulated directly by an APD, and the output of the APD was demodulated again to recover the original base-band signal by the FM demodulator. In the square modulation system, the sub-carrier was square-modulated by the front-end modulator and the doubled sub-carrier was down-converted optically by applying a local signal to the rear end modulator. The transmitted base-band signal of 2kHz was recovered nearly without distortion in both model transmission system.

The experimental results have been suggested the possibility of this method to compose the high-capacity light wave transmission system. If we apply this technique to the conventional light wave transmission system, we may be able to exploit the frequency range which is not used in the present light wave transmission system. In order to apply this system to a presently used optical communication system, a kind of filtering must be employed so that, the signal included in the frequency higher than the cutoff frequency of the photo-detector should not interfere with the base-band signal lower than cutoff frequency. Research of sub-carrier multiplexing systems using a new type filtering to increase the existing optical communication is now undertaken.

REFERENCES

[1] T. Nielsen and S. Chandrasekhar, "OFC 2004 workshop on optical and electronic mitigation of impairments," *J. Lightw. Technol.*, vol. 23, no.1, pp.131-142, Jan. 2005.

[2] A. Farbert, S. Langenbach, N. Stojavic, C. Dorschky, T. Kupfer, C. Schulien, J. P. Elbers, and C. Glingener, " Performance of a 10.7-Gb/s receiver with digital equalizer using maximum likelihood sequence estimation," presented at the *Eur. Conf. Optical Commun.*(ECOC), Stockholm, Sweden, 2004, Paper Th4.1.5.

[3] D. McGhan, C. Laperle, A. Savchenko, C. Li, G. Mak, and M. O'Sullivan, "5120 km RZ-DPSK transmission over G.652 fiber at 10Gb/s with no optical dispersion compensation," presented at the *Optical Fiber Commun. Conf.*(OFC), Anaheim, CA, 2005, Paper PDP27.

[4] K. Kikuchi, "Coherent detection of phase-shift keying signals using digital carrier-phase estimation," presented at the *Optical Fiber Commun. Conf.*(OFC), Anaheim, CA, 2006, Paper OTUI4.

[5] H. Jiang and R. Saunders, "Advances in SeGe ICs for 40 Gb/s signal equalization," Presented at the *Optical Fiber Commun. Conf.*(OFC), Anaheim, CA, 2006, Paper OTUI1.

[6] E. Lach, and K. Schuh, "Recent advances in ultrahigh bit rate ETDM transmission systems," *IEEE J. Lightw. Technol.* Vol. 24. No. 12, pp. 4455-4467, Dec. 2006.

[7] M. Daikoku, I. Morita, H. Taga, H. Tanaka, T. Kawanishi, T. Sakamoto, T. Miyazaki, and T. Fujita, "100Gb/s DQPSK transmission experiment without OTDM for 100G Ethernet transport," presented at the *Optical Fiber Commun. Conf.*, Anaheim, CA, 2006, Post-deadline Paper PDP36.

[8] W. S. Lee. "2.56Tb/s capacity, 0.8b/Hz.s DWDM transmission over 120km NDSF using polarization-bit-interleaved 80Gb/s OTDM signal," in *Proc., OFC, 2001*, pp. TuU1-1-TuU1-4.

[9] W. S. Lee, V. Filsinger, L. Klapproth, H. G. Bach and A. Behling, "Implementation of an 80 Gb/s full ETDM multiformat ASK optical transmitter," presented at the *Proc. ECOC*, pp. 383-384, 2005, Paper We2.2.4. Published by the IEE.

[10] P. J. Winzer, G. Raybon, and M. Duelk, " 107Gb/s optical ETDM transmitter for 100 G Ethernet transport," in *Proc. ECOC*, 2005, pp. 1-2, Post-Deadline Paper Th4.1.1, Published by the *IEE*.

[11] J. C. Campbell, "Recent Advances in Telecommunications Avalanche Photodiodes," *IEEE J. Lightw. Technol.* Vol. 25. No. 1, pp. 109-121, Jan. 2007.

[12] K. Tsuzuki, H. Kikuchi, E. Yamada, H. Yasaka, and T. Ishibashi, "1.3-Vpp push-pull drive InP Mach-Zehnder modulator module for 40Gb/s operation," presented at the *Eur. Conf. Optical Commun.*, Glasgow, U.K., 2005, Paper Th2.6.3.

[13] Y. Muramoto, K. Yoshino, S. Kodama, Y. Hirota, H. Ito, and T. Ishibashi, " 100 and 160Gb/s operation of uni-travelling carrier photodiode module," *Electron. Lett.*, vol. 40, no. 6, pp. 378-380, Mar, 2004.

[14] H. G. Bach, A. Beling, R. Kunkel, G. G. Mekonnen, D. Schmidt, and W. Schelak, " Ultra-high bandwidth optical detectors(100GHz) and monolithic photoreceivers for 80Gb/z NRZ/RZ transmission systems," presented at the at the *Eur. Conf. Optical Commun.* (ECOC), Stockholm, Sweden, 2004, Paper Tu3.1.2.

[15] A. Beling, H. G. Bach, G.G. Mekonnen, R. Kunkel, and D. Schmidt, "Miniaturized waveguide-integrated p-i-n photodetector with 120 GHz bandwidth and high responsivity," *IEEE Photon. Technol. Lett.* Vol. 17, no. 10, pp. 2152-2154, Oct. 2005.

[16] M. Nakajima and T. Kawabata, "A new possibility of wide-band of light communication systems," *1st Optoelectronics Conference* (OEC'86) Technical Digest, Jul. 1986.

[17] M. Nakajima, "High-efficiency light modulator using guided-to-radiation mode coupling : a proposal," *Applied Optics*, vol. 20, No. 14, pp. 2339-2443, Jul. 1991.

[18] H. Mishihara, M. Haruna, and T. Suhara, *Optical Integrated circuits*, McGraw-Hill, pp. 300-301, New York, 1989.

[19] W. K. Kulczyk and Q. V. Davis, "The avalanche photodiode as an electronic mixer in an optical receiver," *IEEE Electron. Device*, vol. ED-19, no. 11, pp. 1181-1190, Dec. 1972.

Young-Kyu Choi
received the B.S. in Electronic Engineering form the Chung-Ang University, Seoul, Korea, in 1982, and M.S. and Ph.D degrees from Kyoto University, Kyoto, Japan in 1989, and 1992, respectively. From 1992 to 1995, he was a full-time lecturer of the Department of Electronics, Fukui University, Fukui, Japan. He is now an associate professor of the Department of Electronics, Silla University, Busan, Korea.