Simultaneous 3-band modulation 2.5-Gb/s baseband, microwave-, and 60-GHz-band signals using a single electroabsorption modulator for radio-on-fiber systems

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Abstract — **A simultaneous modulation using a single 60-GHz-band EAM and fiber-optic transmission of 2.5-Gb/s baseband, microwave-band, and 59.6-GHz 155.52-Mb/s differential-phase-shift-keying (DPSK) signals on a single wavelength and transmission over 40-km-long dispersion-shifted fiber (DSF) are experimentally demonstrated. The optimum 3-band operation conditions are investigated. The degradation due to the non-linearity of the EAM for millimeter-wave signal is also investigated theoretically.**

I. INTRODUCTION

A demand for utilizing broad bandwidth is accelerating in both fixed and mobile access networks. Optical fibers have been applied to various access networks such as Fiber-to-the-Home (FTTH) and Gigabit-Ethernet for fixed terminals. There will be also growing demand for portable or mobile access, that is, *wireless last hop* such as mobile computing, personal digital associates, and cellular phones. Although microwave of 2.4-GHz and 5.2-GHz-bands (IEEE 802.11 b and a) are used for wireless local-area-network (LAN), millimeter-wave is also expected to be the most powerful candidate of radio-frequency (RF) resource for the future wireless access. This is because it can provide broader bandwidth and resolve the scarcity of available RF resources. Radio-on-Fiber (ROF) technique has been studied to realize cost effective millimeter-wave wireless access network. The simultaneous modulation and transmission for two bands of baseband and passband has been reported [1]-[3].

In this paper, we experimentally demonstrate and theoretically analyze a simultaneous multi-band modulation using a single electroabsorption modulator (EAM) and fiber-optic transmission of a 2.5-Gb/s baseband signal, sinusoidal wave of microwave, and 59.6-GHz 155.52-Mb/s differential-phase-shift-keying (DPSK) signal. An electroabsorption modulator (EAM) is a key to the electric-to-optic (E/O) conversion in wide range from dc to 60-GHz-band [4]. Simultaneous modulation of the 10-Gb/s baseband and 60-GHz-band signals has been demonstrated [1]. To the authors' knowledge, this is the first experimental demonstration that the multi-band signals of a 2.5-Gb/s baseband, microwave-band and 60-GHz-band are simultaneously modulated with a single EAM, and the optical signal is transmitted on a single wavelength over a 40-km-long dispersion-shifted fiber (DSF). This technique will be viable for the future access network of FTTH combined with wireless access supported by the radio-on-fiber as the wireless feeder.

II. 3-BAND MODULATION AND TRANSMISSION SCHEME

Figure 1(a) shows the conceptual configuration of the 3-band modulation and transmission. A combined electrical signal of a baseband signal, the microwave and the millimeter-wave band RF signals is applied to the E/O converter as a modulation signal. Another scheme would be a direct modulation of laser diode by the baseband signal, which is followed by the external modulation by simultaneously applying microwave and millimeter-wave signals to a single modulator. Our choice goes for the former simpler 3-band modulation scheme using an E/O converter.

III. EXPERIMENTAL SETUP

Figure 1(b) shows the experimental setup. In the transmitter, a baseband signal (2488.32Mb/s, PRBS=2^{23}-1) is generated from a pulse pattern generator (PPG_1), and filtered by a quasi-Gaussian low-pass filter (LPF) with a cutoff frequency of 2.5 GHz. The bit-error-rate (BER) measurement results in the microwave regime are not available. Instead, the influences of the microwave signal upon the baseband and 59.6-GHz-band signals are investigated by sweeping sinusoidal microwave signal ranging from 4.5 to 12.0 GHz. The sinusoidal wave of microwave is generated from a synthesizer. A 59.6-GHz

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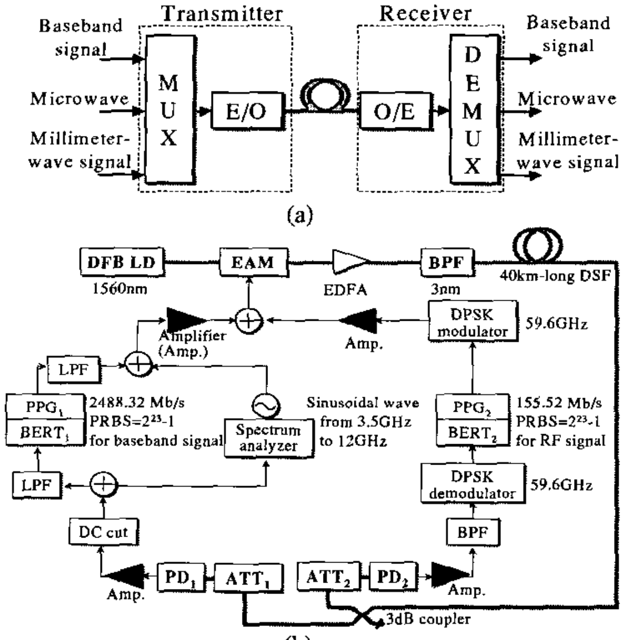

Fig.1. (a) Schematic block diagram and (b) the experimental setup for 3-band modulation and transmission.

RF signal (155.52 Mb/s, PRBS=2^{23}-1) is also generated with another PPG_2 with a DPSK modulator. The sum of the baseband signal and sinusoidal wave in microwave is amplified and combined with the 59.6-GHz RF signal. The optical carrier (λ=1560 nm, 5.0 dBm) is modulated with the special class of 60-GHz-band EAM [4] by applying the combined signal. The bias of the EAM was set to -1.30V, and the input V_{PP} of the baseband and 59.6-GHz band to the EAM was set to 0.487 and 0.456 V, respectively. The input V_{PP} of the microwave to the EAM was varied from 0.112 to 0.674 V. The modulated optical signal is amplified by an erbium-doped fiber amplifier (EDFA). An optical band-pass filter (BPF) suppresses the amplified spontaneous emission (ASE) noise from EDFA. A 40-km-long DSF (λ_0=1560.395 nm) was used as a fiber-optic link for the purpose of reducing the fading problem due to the fiber dispersion. The transmitted optical signals are detected by photodetectors (PDs). Then the 59.6-GHz-band signal was demodulated after passing an electrical BPF to remove the undesired frequency components. Otherwise to regenerate the baseband data the lowpass filter (LPF) suppresses the undesired higher frequency components. The cunning-clock was used to measure the BER of the baseband signal. A 3-dB optical coupler and two PDs were used instead of a PD and an electrical power divider to measure the bit-error-rate (BER) of baseband and 59.6-GHz band simultaneously.

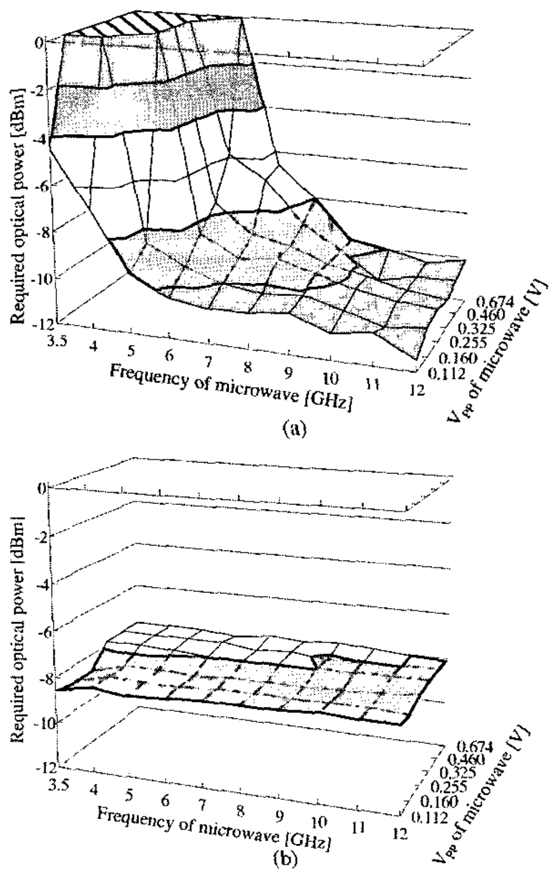

Fig.2. (a) Required optical power of baseband signal to achieve BERs below 10^{-9}. (b) Required optical power of 59.6GHz-band signal to achieve BERs below 10^{-9}.

IV. EXPERIMENTAL RESULTS

We investigated the optimum operation conditions that guarantee the 3-band transmission. Figure 2(a) and (b) show the required optical power of 2.5-Gb/s baseband signal and 59.6-GHz-band signal to achieve BER<10^{-9} as functions of the frequency and the applied voltage of the microwave signal respectively. The microwave was set frequency to 3.5, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0, 11.0 and 12.0 GHz and its V_{PP} was set to 0.112, 0.160, 0.256, 0.325, 0.460 and 0.674 V, respectively. These V_{PP}s were measured at input of the EAM. Note that the BER<10^{-9} of baseband signal was maintained except for the region of low V_{pp} around 4 GHz (oblique lines) in figure 2(a). There was a serious interference between baseband signal and microwave at oblique lines region. Figure 2(b) shows the required optical power of 59.6-GHz-band signal as functions of the frequency and the applied voltage of the microwave signal. Here, the BER<10^{-9} of 59.6-GHz signal is maintained over the entire microwave frequency

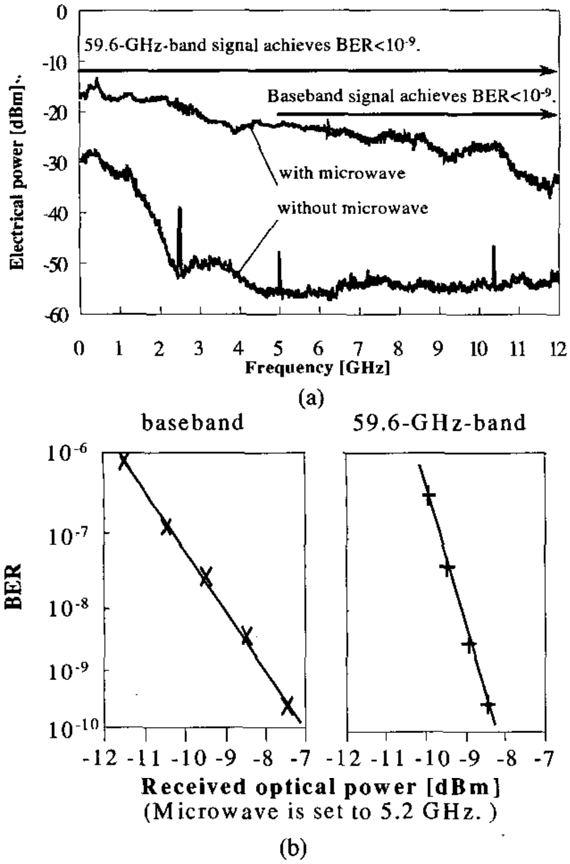

Fig.3. (a) Intensities of swept microwave versus frequency and (b) the BERs.

region. Figure 3(a) shows the measured output power of the PD versus the frequency of applied sinusoidal microwave. The frequency was swept from 10 MHz to 12 GHz, and its V_{PP} was set to 0.160 V. The baseband signal achieved error free of $BER<10^{-9}$ when the frequency of microwave is higher than 5 GHz and its V_{PP} of baseband was set to 0.487 V. And the V_{PP} of 59.6-GHz signal was set to 0.456 V and 59.6-GHz signal always achieved $BER<10^{-9}$. The microwave signal does not have serious effect on the baseband signal when microwave frequency is higher than 5-GHz. This is because in the frequency region above 5-GHz the microwave is suppressed sufficiently by the electrical LPF of the baseband receiver. In the detected 59.6-GHz signal, the microwave is suppressed at the BPF before demodulator of the 59.6-GHz signal. There is no serious problem to the 59.6-GHz signal by the microwave. Therefore, the error-free transmission of baseband and 59.6-GHz signals was simultaneously achieved when the power level of the microwave frequency is optimized.

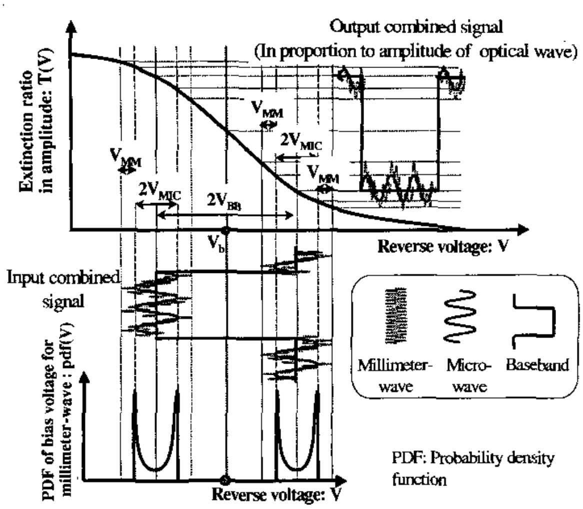

Fig.4. Non-linear extinction ratio and distortion to signal.

In the measurement, the input power of microwave sinusoidal wave was set to -3 dBm. The link efficiency, which is defined as the power ratio of the output and input signals, were about -19 and -21 dB around the baseband and the 5GHz-band, respectively. This shows the feasibility modulation and transmission of the microwave signal with a baseband and 59.6-GHz signals.

V. DISSCUSSION – ESTIMATION OF SIGNAL DEGRADATIONS DUE TO NON-LINEARITY

Figure 4 illustrates the distortion due to the nonlinearity of the EAM. The slope of the extinction ratio of EAM is varied with voltage, which determines the RF modulation depth as well as the extinction ratio of baseband on-off keying signal. The modulation depth of millimeter-wave is varied with the bias voltage, which is the sum of bias voltage V_{bias}, baseband signal and microwave signal even if the same input millimeter-wave signal is used. When the optical carrier is modulated by RF signal with bias voltage V_{bias}, the photocurrent generated at photodetector is [1]

$$I(t) = RP \cdot T_0(V_{bias}) T_1(V_{bias}) \cdot V_{RF} \cos\phi_{RF}(t), \quad (1)$$

where R, $\sqrt{P}$, $T_0(V_{bias})$, $T_1(V_{bias})$, V_{RF}, and ϕ_{RF} are , the photo-sensitivity of the O/E, the amplitude of the optical carrier, the functions related with DC and RF component in the optical signal, the amplitude and the phase of the RF signal, respectively. The bias voltage for millimeter-wave signal is

$$V_{MMbias}(t) = V_b + V_{BB} \cdot b(t) + V_{MIC} \cos(2\pi f_{MIC} t + \theta_{MIC}(t)), \quad (2)$$

where V_b, V_{BB} and V_{MIC} are the bias voltage, the amplitudes of baseband and microwave signals. The V_b is set to provide the highest modulation depth of millimeter-wave. $b(t)[=1,-1]$ and $\theta_{MIC}(t)[=0,\pi]$ are the data for baseband and mm-wave-band signals. The photocurrent for millimeter-wave signal can be estimated as (3) by using (1),

$$I(V_{MMbias}) = RP \cdot T_0(V_{MMbias})T_1(V_{MMbias}) \cdot V_{MM} \cos\phi_{MM}(t), \quad (3)$$

where V_{MM} and ϕ_{MM} are the amplitude and the phase of millimeter-wave, respectively. The probability density function (PDF) of V_{MMbias} is

$$\begin{cases} pdf(V) = \dfrac{1}{2\pi\sqrt{V_{MIC}^2 - \{V - (V_b - V_{BB})\}^2}}, \\ \quad (V_b - V_{BB} - V_{MIC} \le V \le V_b - V_{BB} + V_{MIC}) \\ pdf(V) = \dfrac{1}{2\pi\sqrt{V_{MIC}^2 - \{V - (V_b + V_{BB})\}^2}}, \\ \quad (V_b + V_{BB} - V_{MIC} \le V \le V_b + V_{BB} + V_{MIC}) \\ pdf(V) = 0. \\ \quad (V < V_b - V_{BB} + V_{MIC},\ V_b + V_{BB} + V_{MIC} < V, \\ \quad\quad V_b - V_{BB} + V_{MIC} < V < V_b + V_{BB} - V_{MIC}). \end{cases} \quad (4)$$

The probability of data "1"s and "-1"s of the $b(t)$ is assumed as the same. Taking into account the subcarrier modulation, the power of the photodetected millimeter-wave signal S_{MM} becomes

$$S_{MM} = \int_{-\infty}^{\infty} S(V) \cdot pdf(V) dV, \quad (5)$$

where $S(V)$ is

$$S(V) = R_L \cdot I(V)^2 = R_L \cdot R^2 P^2 \cdot T_0(V)^2 T_1(V)^2 \cdot V_{MM}{}^2/2, \quad (6)$$

and R_L is the load resistance. To estimate the degradation of millimeter-wave signal, we introduce the ratio

$$\Delta S_{MM} \equiv S_{MM} / [S_{MM}]_{V_{BB}=V_{MIC}=0}. \quad (7)$$

Figure 5 shows the numerical result of the degradation of the millimeter-wave signal. ΔS_{MM} decreases as the V_{MIC} becomes larger. In experiment, the input amplitude of microwave was varied from 0.056V to 0.337V. The degradation of ΔS_{MM} was experimentally confirmed as shown in Fig. 2 (b) that as the V_{PP} of the microwave became larger, the required optical power to achieve BER<10^{-9} slightly increased. The theory predicts well this tendency of the experimental results. As a result, it is confirmed both experimentally and theoretically that the simultaneous 3-band modulation can be achieved without inducing serious degradation on each other when each frequency and amplitude are chosen properly.

VI. CONCLUSION

We have experimentally demonstrated and theoretically analyzed simultaneous multi-band modulation using a

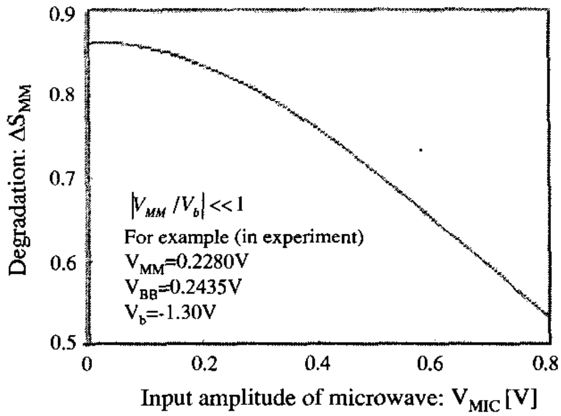

Fig.5. Degradation of millimeter-wave signal.

single EAM and fiber-optic transmission of 2.5-Gb/s baseband, microwave-band and 60-GHz-band radio signals on a single wavelength for the first time. The optimum 3-band operation conditions have been obtained. This technique will be viable for the future access network of FTTH combined with wireless access supported by the radio-on-fiber as the wireless feeder.

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