Super–High Speed Photodetection through Frequency Conversion for Microwave on Optical Network

Young-Kyu Choi and **Sang-Yeol Shin**, *Member, KIMICS*

Abstract— It is shown that even if the modulating frequency of the light is too high for direct detection the signal can be extracted by frequency conversion at the same time as the detection by means of the nonlinearity of the APD. When this frequency conversion detection is applied to an optical receiver, the detection bandwidth can be increased while the configuration of the optical detection circuit and the signal processing in the subsequent stages are simplified. A fundamental analysis is carried out with an APD which is confirmed experimentally.

Index Terms— Photodiode, frequency conversion, optical mixing, photo-detection,

I. INTRODUCTION

Radio-over-fiber systems operating at millimeter wave frequencies are widely studied in the literature for the provision of future wireless-access networks with wider service coverage, broader bandwidth service, and larger channel capacity[1-3]. The typical architecture of a millimeter wave wireless access system with optical-fiber backhaul is shown in Fig.1. In this system the radio signals are generated at a central station and are distributed to and from the radio base stations as millimeter wave modulated optical signals.

Because the each base stations requires a small part of millimeter wave frequency radio signals, this system can cover a lot of base stations. In this case, the radio base station carries out only optical-to-electrical and electrical-to-optical conversion by using optoelectronic mixer. All of the complicated functions such as radio-frequency modulation, demodulation, channel control are implemented in the central station.

There are three types of optoelectronic mixers based on photodiode (p-i-n PD or APD) in the base station ; photo parametric amplifiers[4], an optoelectronic mixer with a microwave reference signal[5-8], and an optoelectronic mixer with an intensity-modulated optical reference signal[9-11]. It is worth noting that the optoelectronic frequency-mixing process in the photodiode has been studied both experimentally[10], [12] and theoretically[11], [13]. In the optoelectronic mixer with a microwave reference signal, frequency conversion occurs due to photodiode responsivity dependence on bias voltage. In other words, the intensity-modulated optical signal is detected by the photodiode with responsivity modulated by the microwave reference signal. This results in intermodulation-product generation.

However, conventionally designed photodiodes have relatively low efficiency of frequency conversion of intensity-modulated optical signals[9], [10]. The studies of optical mixing up to date have been focused only under the cutoff frequency of the photodiode. The frequency characteristics of the photodiodes are not taken into account, and the loss due to frequency conversion is occured in the previous works.

The main goal of this paper is to study the optoelectronic frequency-mixing process of a photodiode and operating regime from the frequency-conversion-efficiency point of view beyond the cut-off frequency of a photodiode. Especially, we consider the optoelectronic mixing by using an APD, because an APD has high sensivity and strong nonlinearities. If we use this method intentionally in the wireless-access networks, it is possible to detect the high frequency signal beyond cutoff region, and to cover a lot of base stations in the wireless system.

This paper is designed in the following way. All kinds of nonlinearities of a photodiode are reviewed in section 2. In section 3, advanced theory of the optoelectronic frequency mixing in the photodiode beyond the cutoff frequency region is analyzed. Experiments of optoelectronic frequency mixing are carried out in section 4. In section 5, we discuss the experimental results in comparing with theoretical analysis.

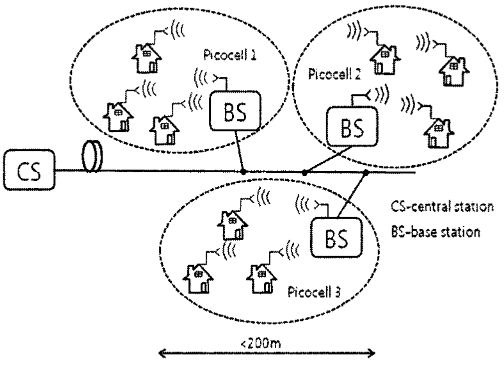

Fig.1 Typical architecture of a radio-over-fiber system.

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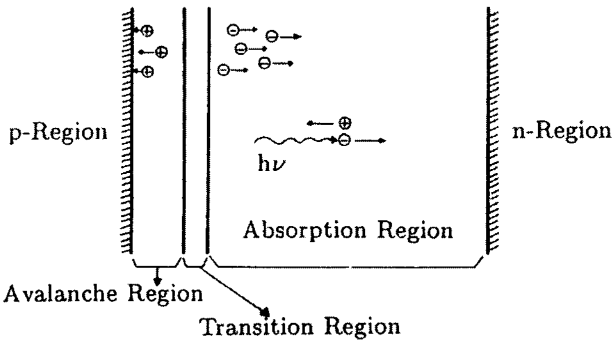

Fig.2 Schematic cross-section of APD.

II. NONLINERAITY OF PHOTODIODE

An APD which operates at high sensitivity at a high speed has a configuration in which the optical detection region and the amplification region are separated. A general APD model is shown in Fig. 2. The electron-hole pairs generated in the absorption region are separated by a high electric field applied to the depletion region so that the holes are diverted to the p-region and the electrons to the n-region. Holes with a high energy accelerated by a high electric field enter the multiplication region and generate new electron-hole pairs.

When the carriers are generated by optical absorption in the absorption region, the drift velocity and the avalanche multiplication factor change nonlinearly depending on the intensity of the bias electric field applied to the depletion region. When the generated optical carriers flow in the diodes as the photo current, the current-voltage characteristics as a diode are exhibited. Further, the width of the depletion region and the internal capacitance vary nonlinearly by the bias voltage. The relationships of these characteristics to the bias voltage are listed in Table 1.

Table 1. Bias voltage characteristics of a photodiode.

Drift velocity	$v_n = \mu_n E$, $v_p = \mu_p E$
Inner capacitance	$C=C_o(1-v/V_D)^{-n}$ (n=1/2~ 1/3
Width of depletion layer	$\Phi=\Phi_o(V_D-V)^n$ (n=1/2~1/3)
Multiplication coefficient	$M = \frac{1}{1-(v/V_B)^n}$ $(n = 3\sim6)$
Diode I-V characteristics	$I = I_s\left(e^{ev/kt} - 1\right)$

Here, V is the voltage applied to the diode while E is the resultant electric field. In the optical detection, these characteristics affect the output of the optical signal and the frequency response of the optical detector. When the bias voltage is modulated with the local radio signal at the time of the optical detection, the optical signal and the local radio signal are mixed in the APD so that a frequency conversion takes place. In this case, if the subcarrier method is used, the original signal is contained either in the frequency or in the phase of the subcarrier as seen in Eq.(7) later. Therefore, the original signal can be extracted without distortion as the difference frequency component converted to a lower frequency. In this paper, among the nonlinearities, the largest one in the APD, or the relationship between the multiplication factor and the bias voltage, is chosen and is applied to optical detection.

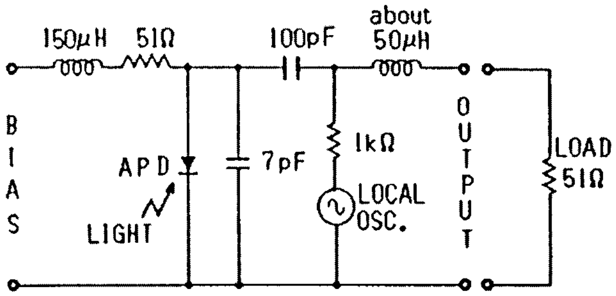

Fig.3 Frequency conversion photodetection circuit using an APD(7pF capacitor is for the experiment beyond cutoff frequency).

III. FREQUENCY CONCERSION THEORY

The optical detection circuit used for the experiment is shown in Fig. 3. Let us consider the case in which an APD is used. When the light intensity modulated with the signal of the subcarrier frequency f_s, the modulation index of $|m|$ and the phase $\theta(t)$

$$P(t) = P_o[1 + |m|\, cos\{2\pi f_s t + \theta(t)\}] \qquad (1)$$

is incident (where $P_o$is the dc light), then a photo current flow in the APD is

$$I_p(t) = M(v)\eta' P_o[1 + |m|\, cos\{2\pi f t + \theta(t)\}] \qquad (2)$$

where $M(v)$ is the multiplication factor of the APD, and η' is expressed by

$$\eta' = \left(\frac{e}{hv}\right)\eta_p \eta_c \qquad (3)$$

here, η' is the efficiency of the photo detector, η_p is the efficiency in the particle state and η_c is the efficiency of the electronic circuit system. If the intensity $V_l$of the bias voltage $v(t)$ across the APD modulated with the local radio signal at a frequency of f_{lo}, then

$$v(t) = V_b + V_l cos 2\pi f_{lo} t\,. \qquad (4)$$

Since the multiplication factor $M(v)$ of the carriers in the APD empirically given in terms of the bias voltage as

$$M(v) = \frac{V_b}{1 - \left({}^{v(t)}/_{V_B}\right)^n} \qquad (n = 3\sim6) \qquad (5)$$

then substitution of Eq.(4) into Eq.(5) and expansion in a Taylor series near V_b give

$$M = M(V_b) + M'(V_b)V_l cos2\pi f_{lo}t + \cdots \quad (6)$$

where $M' = dM/dV$. When Eq.(6) is substituted into Eq.(2), the photo current is

$$\begin{aligned} I_p(t) = M(V_b)P_o\eta' \Big[& 1 + |m| cos\{2\pi f_s t + \theta(t)\} \\ & + \frac{M'(V_b)}{M(V_b)} V_l cos2\pi f_{lo}t \\ & + \frac{1}{2}|m|\frac{M'(V_b)}{M(V_b)} V_l cos\,\{2\pi(f_s \pm f_m) \\ & + \theta(t)\} + \cdots \Big] \end{aligned} \quad (7)$$

In addition to the signal frequency f_s, frequency components $f_\pm = f_s \pm f_{lo}$ also appear in Eq.(7). Usually, the detected optical signal current is bypassed by the internal capacitance between the APD terminals so that the apparent quantum efficiency is decreased as the frequency is increased. Hence, η_c can be expressed as a function of frequency such as $\eta_c(f_s)$ or $\eta_c(f_-)$. Hence, the ratio of the magnitude of the f_- signal to the f_s signal can be written as

$$g = \left|\frac{M'(V_b)V_l}{2M(V_b)}\right| \frac{\eta_c(f_-)}{\eta_c(f_s)} \quad (8)$$

If the dc bias V_b is set near the breakdown voltage V_B, $|M'(V_b)V_l/2M(V_b)|$ in Eq.(8) increases without limit. If on the other hand the local oscillator signal f_{lo} is chosen such that $f_-(= f_s - f_l)$ is sufficiently small, the electronic circuit quantum efficiency $\eta_c(f_-)$ can be made to be near a constant value $\eta_c(0) = 1$. Hence, if the modulation frequency f_s is higher than the bandwidth of the optical detector, $\eta_c(f_s)$ is small and then an efficient optical detection is possible in a relative sense if the f_- frequency component is extracted as an output instead of the f_s frequency component. Therefore, Eq.(8) can be called the frequency conversion gain of the optical detection method of this type.

IV. EXPERIMENTAL RESULTS

We fabricated the detection circuit with an APD(FU-04AP-N by Mitsubishi) as is shown in Fig. 3. The optical source for the detection experiment was a short wavelength laser (FU-01 LD-N, wavelength 0.85μm by Mitsubishi) modulated directly. The configuration of the experimental setup is shown in Fig.4. The modulated light is divided by an optical divider and the output of the optical detector circuit was measured with a spectrum analyzer while the modulation index is monitored with an optical oscilloscope.

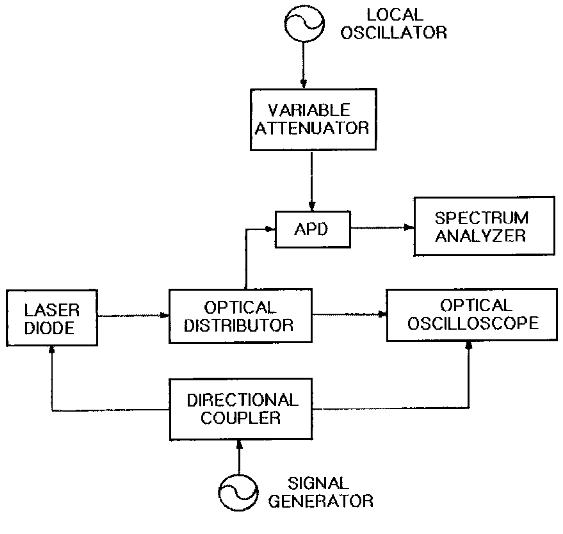

Fig.4 Experimental setup.

Since it is expected that the efficiency of the frequency conversion detection differs in the regions above and the cutoff frequency of the APD, these two cases were measured separately.

Because the 3 dB cutoff frequency of the APD was 2 GHz, the optical detection experiment was carried out for the light modulated at 1.3 GHz which is within the detection bandwidth of the APD. In this experiment, the bias voltage V_b of the APD was always fixed at 116V. By applying the local microwave signal of 1.26 GHz, the differences output of 40MHz was measured. The relationship between the local signal input and the difference component output was shown in Fig. 5. When a local signal of more than 20dBm is applied, the output of the difference frequency component became larger than the directly detected output. The characteristics of the difference frequency was shown in Fig. 6. We know that the smaller the difference frequency is, the larger the output of the difference component is.

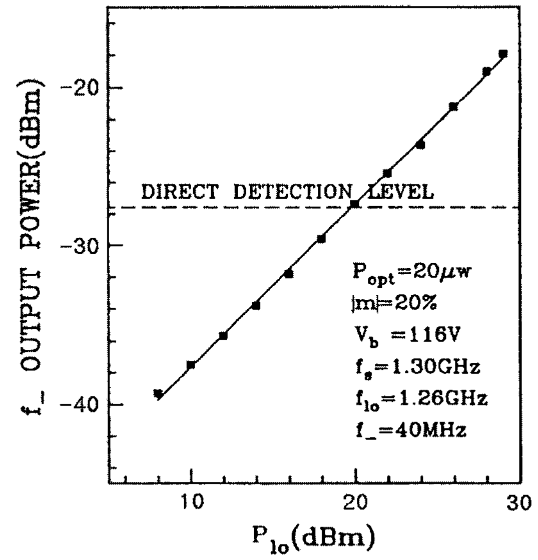

Fig.5 The relation of difference frequency component power and local signal power.

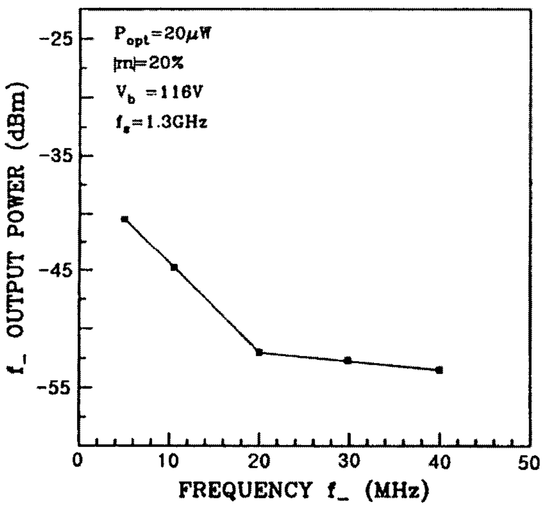

Fig.6 Difference frequency vs. output power

Next, if the frequency is more higher than the bandwidth, a 7pF capacitor is added in parallel to the APD so that the high frequency characteristics of the detection circuit are reduced. The frequency characteristics of the detection circuit with a capacitor inserted was shown in Fig. 3. The results indicated negligible direct detection output at frequencies over 700MHz. By choosing 780 MHz for which the direction output is the smallest, we applied a local microwave signal at 1.26 GHz so that the difference component output at 480 MHz was measured. The results were shown in Fig. 7. For the local signal of 10-20dBm, the difference component output of about 10dBm was obtained. In this case, the output also increases with the local signal input.

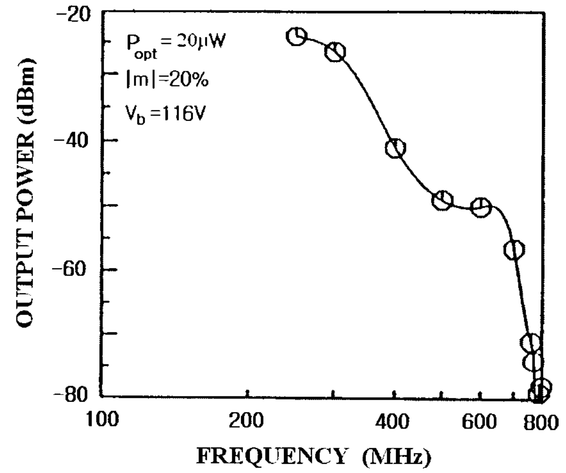

Fig.6 Frequency response of the detection circuit which 7pF capacitor is added in parallel.

V. DICUSSIONS

The above experimental results qualitatively agree with the results of the fundamental analysis Eq. (8). First, in the experiment at frequencies under the detection bandwidth, the frequency conversion gain exceeds one for the local signal input of more than 20dBm. It was also confirmed that η_c increases as the difference component frequency f_- is lower. In the case of higher frequency than cutoff, $\eta_c(f_s)$ further decreases. Hence, $\eta_c(f_-)/\eta_c(f_s)$ increases so that the frequency conversion gain larger than one can be obtained even for a local signal smaller than the detection bandwidth. It may be concluded that a larger conversion efficiency is obtained with a small local signal if the modulation frequency is higher.

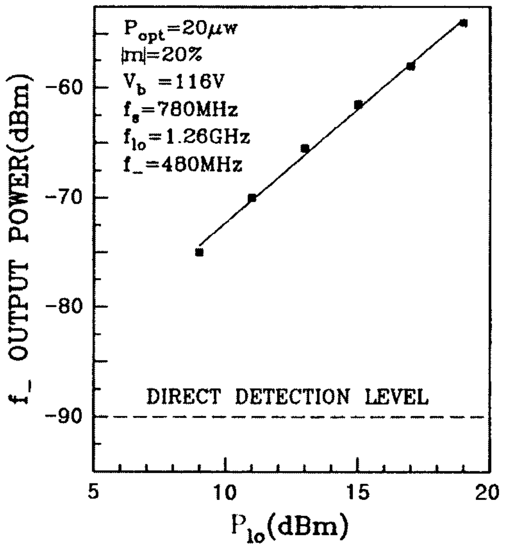

Fig.7 The relation between difference frequency component power and local signal power(beyond the cut-off frequency of the APD).

In the optical mixing experiment beyond the cutoff, a 7pF capacitor was inserted in parallel to the APD so that the frequency at which the APD is capable of direct detection. Experiments with a further higher frequency is desirable in the future.

V. CONCLUSIONS

It was shown to be possible to detect the light modulated with a high frequency signal at a frequency higher than the cutoff with a higher efficiency than the direct detection if the frequency conversion due to nonlinearity of the APD is carried out. If this method is explored further, extension of the detection bandwidth of a usual photodiode is possible. Consequently, this system can cover a lot of base stations in the wireless access networks with optical-fiber backhaul.

In the fundamental analysis carried out here, frequency characteristics of the multiplication factor of the APD, the efficiency at the particle stage and the frequency characteristics of η_p are not taken into consideration. More detailed theoretical and experimental discussions on the mechanism of the optical mixing including these problems need to be carried out in the future.

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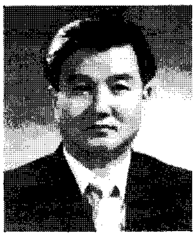

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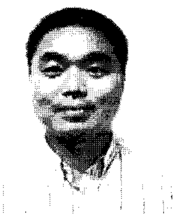

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