5-3 Photonic Antennas and its Application to Radio-over-Fiber Wireless Communication Systems

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In this paper, we presented our recent works on development of photonic feeding coplanar patch antennas for microwave and millimeter-wave wireless communication system. An experiment setup for optical modulation of sub-carrier, photodetection of the sub-carrier-modulated optical wave and integration of the photodetector with a coplanar patch antenna have been described. Experimental results of optical modulation using a traveling-wave $LiNbO_3$ optical modulator, RF output from a photodetector: UTC-PD, and the RF output dependence on modulation index have been presented and discussed. The experiment showed that the photodetector can generate relatively large RF power at microwave and millimeter-wave frequencies, for example, more than 10 mW at both 10 GHz and 20 GHz and around 10 mW at 38 GHz and 7 mW at 60 GHz. Based on this experimental fact, we introduced a concept of direct integration of an antenna with the photodector to realize a simple photonic feeding RF radiation unit to avoid serious transmission loss and simplify the RF system especially in high frequency wireless system. A planar antenna: coplanar patch antenna was newly proposed and designed for the direct integration with the phototector which is of a coplanar wavegide output structure. Simulation, design, fabrication and measurement have been done for the antennas. Experiment on a hybrid integration of the photodetector and the coplanar patch antenna demonstrated a good performance of photonic microwave generating, direct feeding, transmitting and receiving. The results clearly showed the effectiveness and the potential application of our integration configuration to the future microwave and millimeter-wave wireless communication system based on the optical fiber network.

Keywords

High output photodetection, Photodetector, Photonic feeding antenna, Coplanar patch antenna (CPA), Radio-over-fiber

1 Introduction

The modern communication systems are all constructed based on the optical fiber network. Not only the traditional wire communication systems but recently a wireless system, which uses the optical fiber to transmit the radio wave, are under developing [1]. This system is a fusion of the fiber network in which optical wave is used as a carrier and the wireless system in which the radio wave is the major communication media. Optical fiber communication system is of great advantages. It can be high speed and large capacity. The wireless communication system, on the other hand, taking the mobile phone as a good example, has been becoming more and more popular in last decade because its mobility and convenience. The new system, sometimes called radio-over-fiber system, is trying to take the advantages of the above two systems. To realize the system, in additional to exploiting the technologies developed in the two systems, novel technologies which makes the system really attractive by taking both advantages of the radio wave and optical wave are strongly required. This is actually the major research issue of the relative new field, so-called microwave photonics or millimeter-wave photonics. There are several key devices in the system: modulator, which modulates the radio wave on the optical wave; photodetector, which detects the radio wave back from the optical carrier; and antenna, which radiates and receives the radio wave into/from the space. The radio-over-fiber system consists of these key devices.

The main objective of this research work is to develop above devices, especially the devices which can operate efficiently at high frequencies as millimeter-wave. In this work, we have successfully completed a photodetection experiment where we have obtained high RF (Radio Frequency) from a photodetector (PD). After that we started the research of planar antenna, trying to integrate the antenna and the photodetector. Based on the experimental fact, we now introduced a concept: photonic feeding antenna, where the antenna is fed, not by a RF source as usual, but by a photonic device which receives optical wave and generated RF signal from the optical wave [2][3]. This concept is now receiving the attention of the researchers in the microwave photonics and the device, photonic feeding antenna, is expected as a novel key functional device of the next generation microwave and millimeter-wave wireless communication system. In a system with the photonic feeding antenna, the RF signal, as sub-carrier of real signals, is modulated on optical wave by an optical modulator and propagates though an optical fiber. The optical wave reaches a photodetector and is detected with a RF output at the device. The RF signal feeds the integrated antenna and is then radiated by the antenna. It is not necessary to implement transmission lines and RF circuits such as amplifier in the system when the detected RF power is high enough for a system. This avoids serious transmission and processing loss and complicated RF configuration in the system especially at the millimeter-wave frequencies and also makes the system very simple and then potentially low cost. The photodetector used in this work is UTC-PD (Uni-Traveling Carrier Photodiode) [4]. In this paper, we first present our recently obtained experimental results on modulation and photodetection using UTC-PD. Then we describe a new planar antenna, coplanar patch antenna (CPA) [5][6], which is recently developed for the direct integration with the UTC-PD, including its principle, simulation and measured results. Finally, we present the results of a system experiment where we use the concept of photonic feeding antenna to demonstrate the system performance.

2 High RF output photodetection

2.1 Experimental setup for optical modulation, photodetection and photonic feeding antenna

Figure 1 shows an experimental setup for optical modulation using an optical modulator, detection using a photodiode, and radiation and transmission using a CPA and a standard horn antenna. The light source is a laser diode (LD) at 1.55 μm. The optical modulator is a $LiNbO_3$ traveling-wave optical modulator with 3 dB bandwidth of 40 GHz, and can also operate extent to 60 GHz but with much lower response. The photodiode used in the photodetection is an wide band device called uni-traveling-carrier photodiode (UTC-PD) [4]. This photodiode can not only operate over 100 GHz but also can handle a relatively large input optical power. The optical wave is modulated by the microwave or millimeter-wave (MMW) sub-carrier, which is fed from an RF generator and amplified up to about 20 dBm, through the optical modulator and then amplified by an optical amplifier (EDFA) with an output up to 20 dBm. Bias voltage applied to PD is kept at -2.5 V. The RF output from the

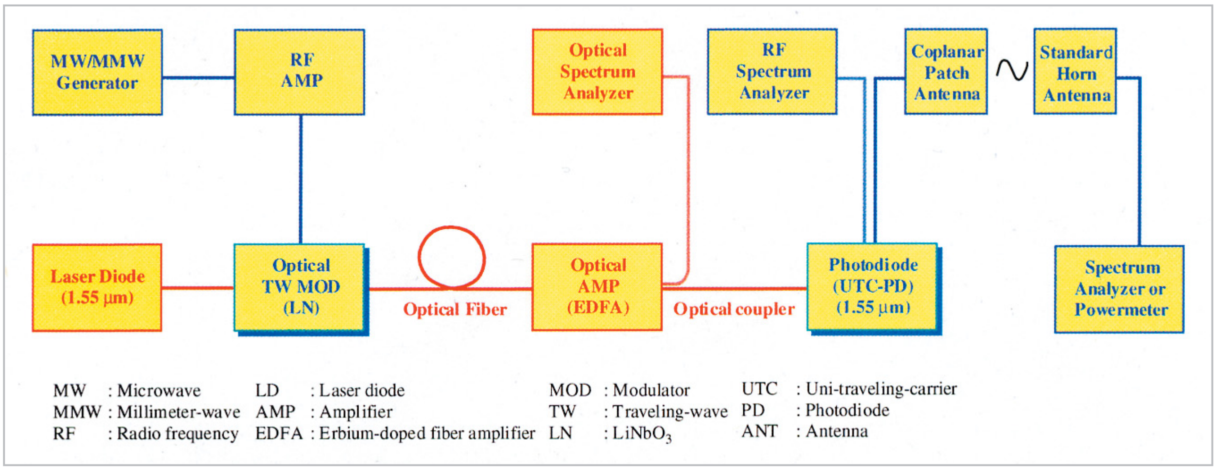


Fig. 1 Experimental setup of optical modulation using an optical modulator, detection using a photodiode, radiation using coplanar patch antenna and receiving using a standard horn antenna.

PD and power received at the standard horn are measured on a spectrum analyzer. The distance between the radiating CPA to the receiving horn is fixed at 75 cm in this experiment.

2.2 Optical modulation and photodetection results

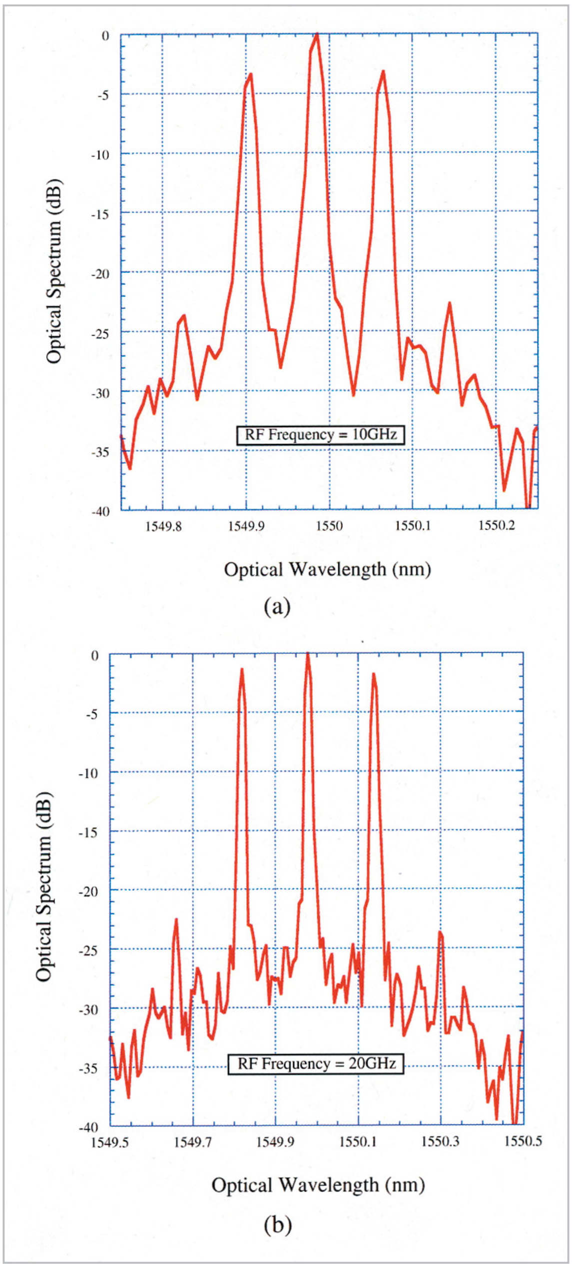
Figure 2 shows the optical spectra of modulated optical waves at 10 GHz and 20 GHz. The modulation indices for each sub-carrier are adjusted by changing the bias voltage applied to the modulator. The photodetection output directly depends on the modulation index, and in our experiment, modulation sidelobes about 3 dB lower than the central carrier peak give a maximum output. This is consistent with the theoretical analysis for a Mach-Zehnder interferometer type modulator. The RF outputs at 10 and 20 GHz versus input optical power into the PD are shown in Fig.3. These results show a relatively large power of more than 10 dBm at both 10 GHz and 20 GHz from the PD, which are close to or even larger than the required power for direct feeding a typical indoor millimeter-wave radiation system. At millimeter-wave frequencies, we have also obtained the relatively larger RF power in experiment as 10 mW at 38 GHz and 7 mW at 60 GHz, respectively. This provides a possibility to construct a simple microwave and millimeter-wave radio-over-fiber systems.

3 Consideration of photonic feeding antenna

With the relatively large RF output power obtained from the experiment, we now consider a direct integration with antenna in order to construct a simple photonic feeding and RF radiation antenna system. Figure 4 shows a basic configuration of the photonic feeding antenna where the PD generates RF signal from the optical wave, and then feeds a planar antenna. Since the UTC-PD has a output structure of coplanar waveguide, so very naturally this system requires a planar antenna with a coplanar fed structure in order to directly connect to the device. We have developed a new antenna, as shown in Fig.5, called coplanar patch antenna (CPA) for the system, which has a coplanar waveguide fed line to connect to the PD and a coplanar patch for radiation. In next sections, we will describe the principle of the CPA, simulation and measured results of the CPA performance, including a two-element CPA array.

3.1 Coplanar patch antenna (CPA) and array [5][6]

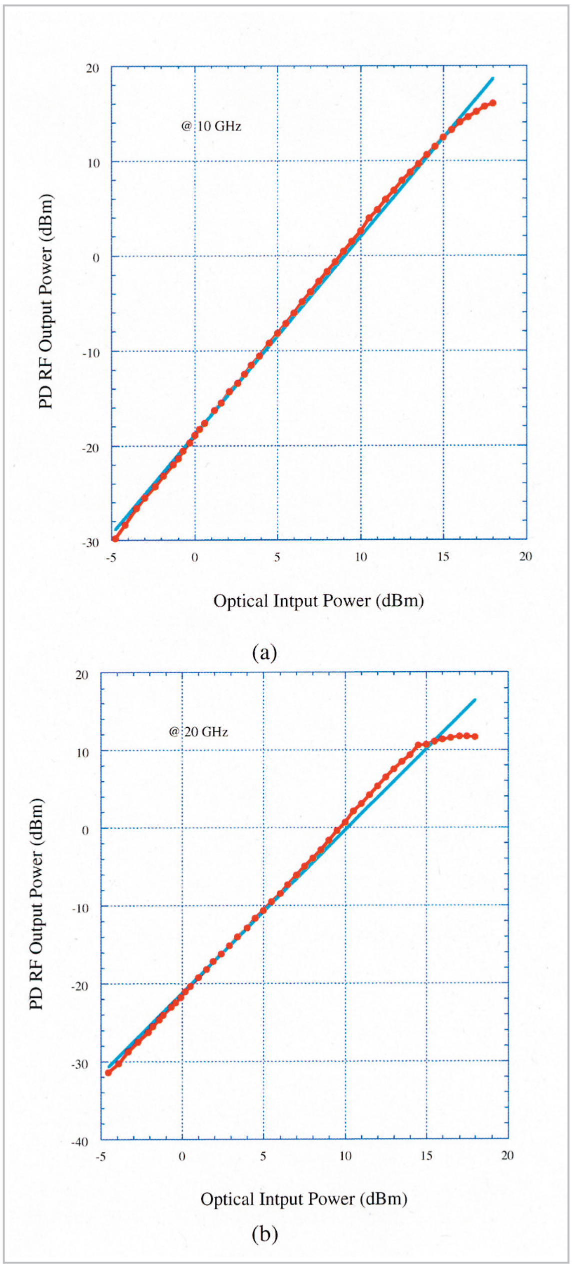
Figure 5 shows the configuration of the proposed CPA which consists of a patch surrounded by closely spaced ground conductor and a coplanar fed line with a back ground



(a)

(b)

Fig.2 Optical spectra of optical wave modulated at (a) 10 GHz and (b) 20 GHz



(a)

(b)

Fig.3 RF output from photodetectors at (a) 10 GHz and (b) 20 GHz

conductor for obtaining unidirectional radiation pattern. The antenna looks very similar to the loop slot antenna as given in [7]-[9]. In fact, the antennas with similar configuration were called as loop slot antennas in [8][9]. From our intensive electromagnetic field simulations of the structure, however, we discovered that the antenna behaves more like a microstrip patch antenna than a loop slot antenna. Particularly, the resonant frequency of the antenna is primarily determined by the patch length (L) of about a half guided wavelength instead of the total loop size. Electromagnetic simulation also demonstrated the similar distribution of the electric fields around the slots as the distribution around the microstrip patch edges. Figure 6 shows the electric field distribution along the slots at the resonant frequency point of 10 GHz. The fields along the feed side slot and outer side slot are in phase and of almost uniform distribution in the horizontal direction. No field changes to be out phase along both the input side and outer side slots though an equivalent

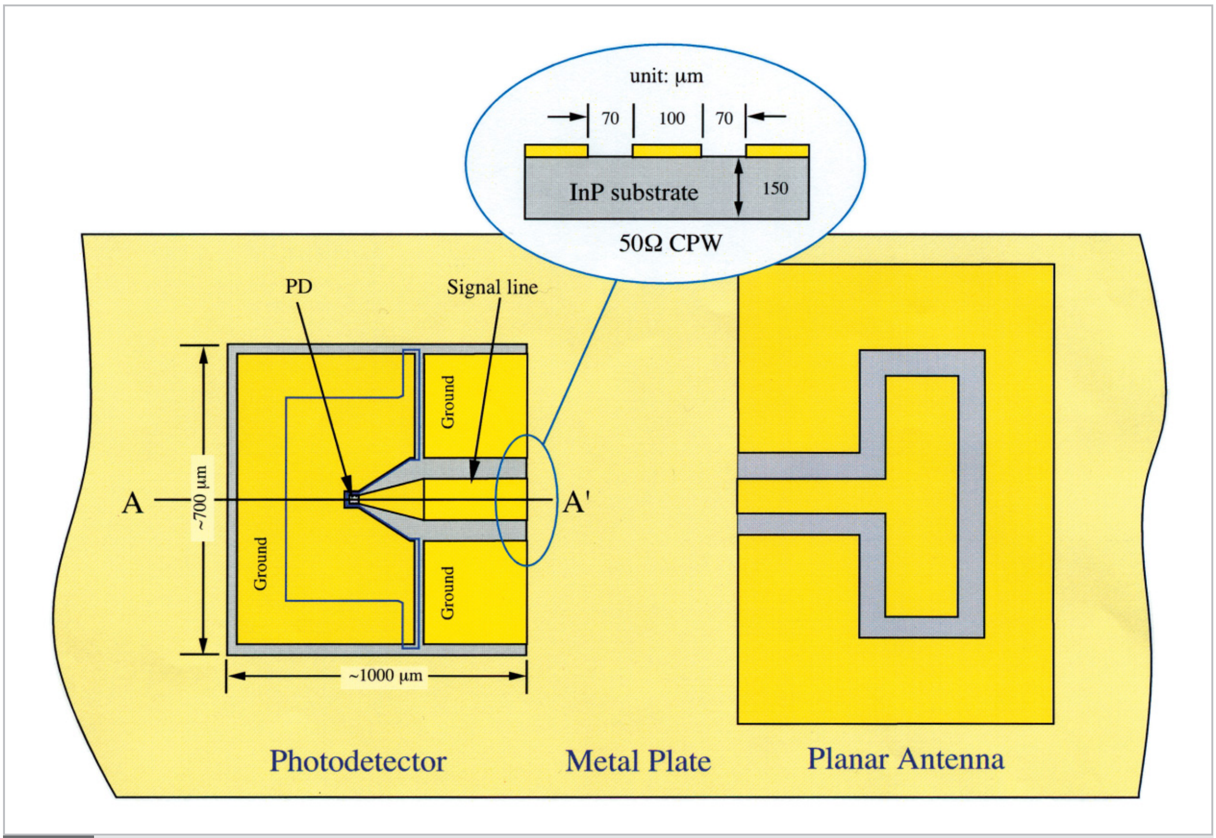


Fig.4 Configuration of a photodetector and a planar antenna to be integrated with the PD

total length of the slot $W + S$ at outer side is about $1.6\lambda_0/\sqrt{\varepsilon_r}$, where λ_0 is the wavelength in free space at 10 GHz, is longer than one and a half guided wavelength, while the fields along the left and right side slots show an out phase variation where the equivalent length of the slots $S/2 + L + S/2$ is about $0.52\lambda_0/\sqrt{\varepsilon_r}$, close to a half of guided wavelength. This field distribution clearly demonstrates that, with the field distribution of the microstrip patch in the mind, the coplanar patch antenna at the resonant point is much more like a "patch" than a "loop slot". The resonant length of coplanar patch $L \approx 0.47\lambda_0/\sqrt{\varepsilon_r} \approx 1/2\lambda_0/\sqrt{\varepsilon_r}$ also follows the same rule as for the microstrip patch antenna. This is why we called the antenna shown in Fig.5 a "coplanar patch" antenna not a "loop slot" antenna.

Similar tendency of the input impedance versus the length (L) of the patch has been also observed. This makes possible to realize an impedance matching by only adjusting the width (W) of the patch. Based on above facts, we introduced a new concept of "coplanar patch antenna (CPA)" in our previous paper [5][6]. By introducing this concept, one can exploit techniques well developed for the microstrip patch antennas by using the similarities between the CPA and microstrip patch antenna.

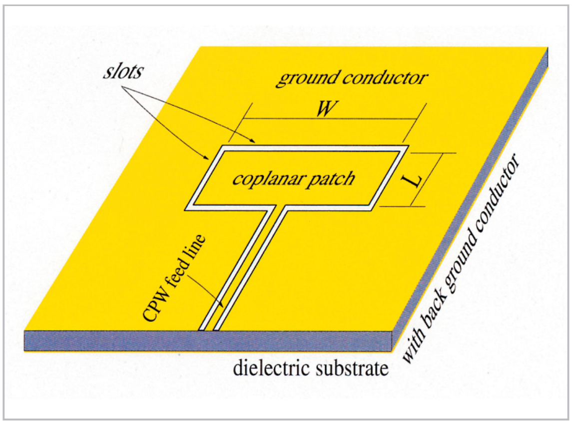


Fig.5 Coplanar patch antenna (CPA) with a coplanar feeding structure

3.2 Simulation and experimental results

To demonstrate the antenna performance

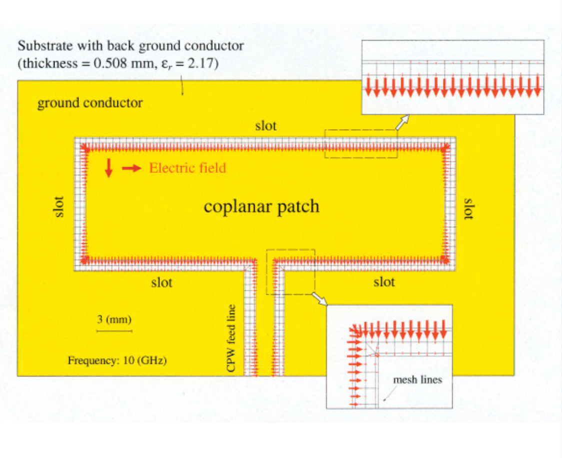


Fig.6 Electric field distribution along the slots in CPA

of the proposed CPA, we have designed, fabricated and measured CPAs at X-band. An two-element CPA array has been also developed to improve the gain of the CPA. The parameters for the substrate and the CPA and array used in this work are listed in Table 1.

Figure 7 and 8 show the return loss and radiation patterns of the CPA. The antenna has about 3.4 % relative bandwidth and 7.8 dBi measured gain.

Figure 9 is the return loss and radiation patterns of the CPA array. The bandwidth is almost the same as a CPA while the measured gain is about 10.5 dBi, 2.7 dB improved comparing with the single CPA. This CPA array was used in the photonic feeding and transmitting experiment shown in Fig.1.

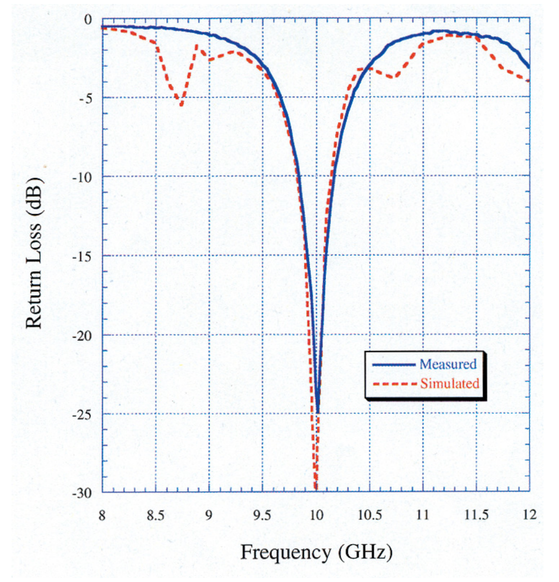
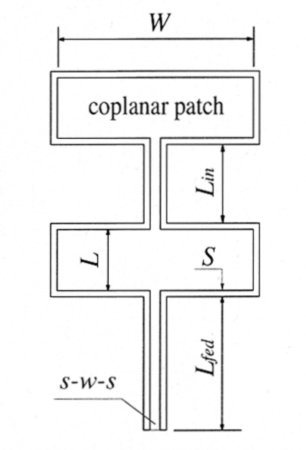


Fig.7 Simulated and measured return loss of CPA (at 10 GHz)

4 Photonic feeding antenna and transmitting experiment

Following the experimental configuration shown in Fig.1, we directly fed the CPA array using the photodetector without any RF amplifier or extra circuit between the antenna and PD. The RF power was then generated by the PD from input optical waves and radiated by the CPA array. The radiated power was received by a standard horn antenna, which has a gain of 11.2 dB at 10 GHz and was located at distance 75 cm from the array. The received power as well as the power after the

Table 1 Parameters of dielectric substrate and geometrical dimensions of CPA and CPA array at 10 GHz

Dielectric substrate (DICLAD®880, ARLON)	ε_r	tan δ (@10GHz)	Thickness of substrate	Metal film	
	2.17	0.00085	0.508	Cu, 18 μm	
Feed line (coplanar waveguide)	s-w-s	L_{fed}	Unit: mm		
	1.0-1.6-1.0	10			
CPA (coplanar patch antenna)	L	W	S	---	
	9.55	31.0	1.0	---	
CPA array	L	W	S	L_{in}	
	9.55	23.0	1.0	8.5	

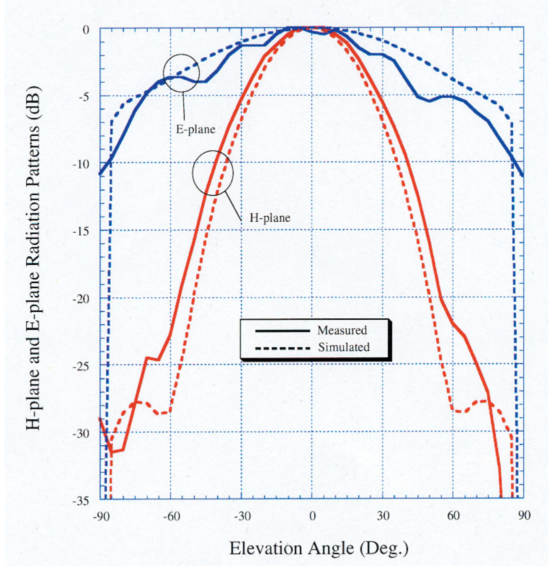


Fig.8 Simulated and measured patterns of CPA (at 10 GHz)

PD are shown in Fig.10. At 10 dBm optical input, for example, the received power is about -22 dBm, which is a large enough value for a conventional wireless system. This result confirms our consideration again that we can use the optical power to overcome the weakness of the microwave and millimeter-wave and construct a simple radio-over-fiber system by using the concept of photonic feeding antenna. Figure 11 shows two measured waveforms of the modulating signal (CW) from the RF source and the output signal from the PD. From this result, we can see that there is no significant signal distortion due to the system.

5 Conclusion

In this paper, we have presented an experiment on optical modulation and photodetection at microwave and millimeter-wave frequencies. The experimental results showed that we can obtain a relatively large power of more than 10 dBm at both 10 GHz and 20 GHz from the photodetector and we can then construct a simple photonic feeding antenna system. A CPA has been developed and used as radiating antenna, which has a CPW fed line matching to the PD and has been designed based on a concept of coplanar patch introduced in [5][6]. The transmitting experiment demonstrated the effectiveness and usefulness of the concept of the photonic feeding antenna and its potential application to the real radio-over-fiber system. This simple configuration would provide a good solution and become a key technology for the future photonic and microwave/millimeter-wave wireless communication systems.

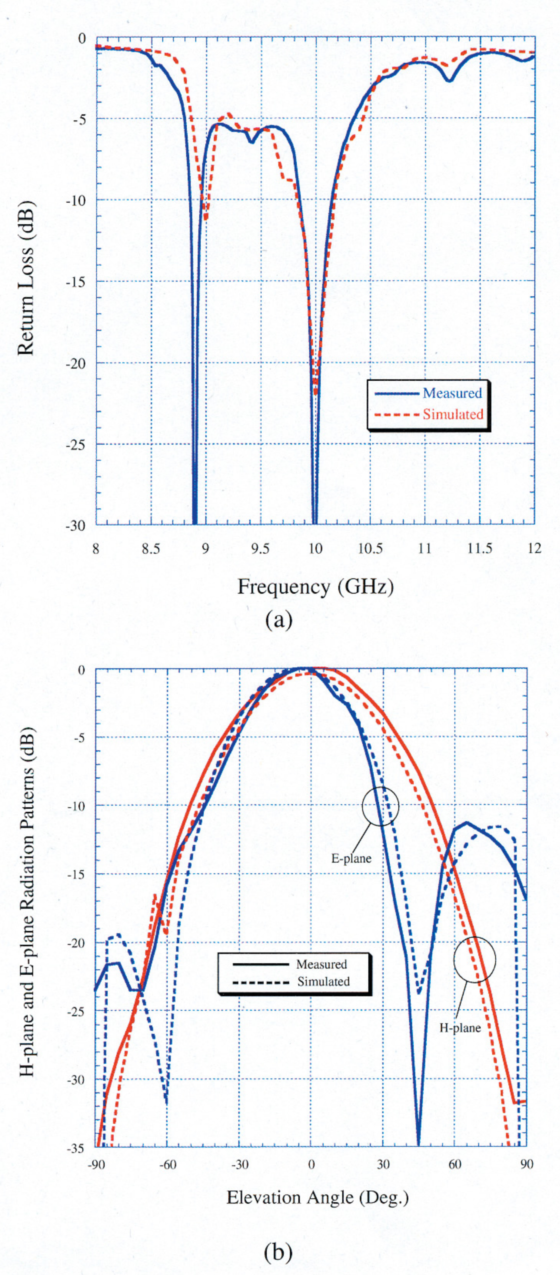


Fig.9 Simulated and measured return loss and patterns of CPA array (at 10 GHz)

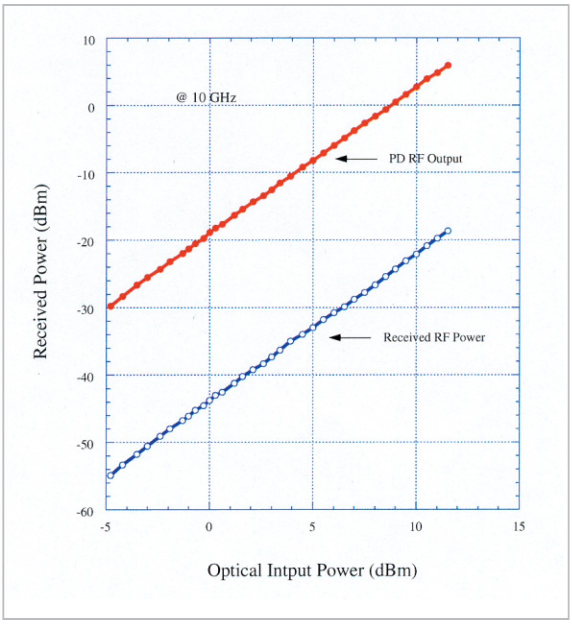


Fig.10 RF power generated by PD and received by horn antenna

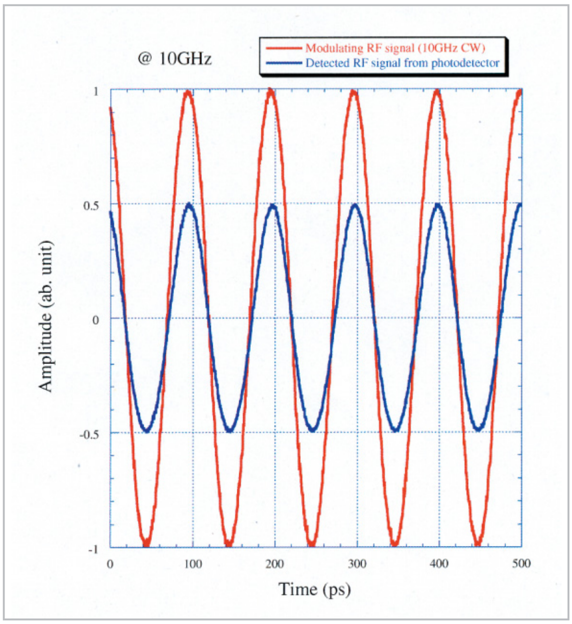


Fig.11 Waveform of the modulating signal (CW) and output signal from the PD

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