Microstrip Patch Antennas Feed to Optical Waveguides in Electro-Optic Modulator for Millimeter-Wave Radar System

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Abstract — Microstrip patch antennas feed to optical waveguides in an electro-optic (EO) modulator are proposed for millimeter-wave radar system. Reflected millimeter-wave radar signals can be received by the microstrip patch antennas and converted directly to lighwave signals through EO modulation. The lightwave signals can be distributed using low loss optical fibers. Millimeter-wave loss and distortion are almost negligible. Device analysis and experiment for 40GHz millimeter-wave bands are discussed.

Index Terms — Microstrip patch antenna, optical waveguide, electro-optic modulator, millimeter-wave bands, radar system.

I. Introduction

Radar systems have been developed and established for defend and military applications in microwave bands [1]. Recently, the microwave radar systems are widely used for field surveillance and weather forecasting. However, microwave bands in the electromagnetic-wave spectrum have relatively narrow bandwidth and no available spectrum more. In order to improve the bandwidth, new electromagnetic-wave spectra in millimeter-wave or terra-hertz bands are potential candidate for radar applications [2]. By using high operational frequency, precise and accurate detection can be obtained.

The millimeter-wave signal is relatively large propagation loss in the air and metal cables. Large detection area can be obtained by networking the millimeter-wave radars. The millimeter-wave radar networks are effectively developed with radio-over-fiber (ROF) technology by low propagation loss optical fibers to compensate for the millimeter-wave losses [3].

In the millimeter-wave radars with ROF technology, millimeter-wave antennas and converters between millimeter-wave and lightwave signals are important devices for front-end units. A high-speed optical photo-detector and millimeter-wave antenna are used for radar signal uplinks to the air. In contrary, a millimeter-wave antenna and high-speed optical modulator are used for radar signal downlinks.

Millimeter-wave antennas have relatively small size with several antenna types and feeding techniques. One antenna type with simple and easy in design and fabrication is microstrip antennas in planar structures with moderate gain and bandwidth [4]. Several feeding techniques are useable in the microstrip antennas using millimeter-wave metal cables and planar connection lines.

In millimeter-wave radar signal downlink, the microstrip antennas with feeding can be combined discretely with optical modulators through electro-optic (EO) modulation [5]. In this structure, millimeter-wave losses and distortion might be induced along the millimeter-wave connection line and coupling. In order to reduce the losses, microstrip millimeter-wave antennas can be integrated with EO modulators in the same substrate [6,7]. The microstrip antennas are connected to planar modulation electrodes using microstrip connection lines. Simple and compact structures are obtained with low millimeter-wave losses. The integrated devices require good matching condition between the microstrip structures with consideration of precise tuning. The precise tuning are rather difficult since the operational frequency is high. Therefore millimeter-wave distortion might be still induced through their coupling.

In this paper, a millimeter-wave radar downlink using microstrip patch antennas feed to optical waveguides in an EO modulator is proposed. The proposed device is composed of microstrip patch antennas for receiving millimeter-wave radar signals and optical waveguides on the antennas for converting the millimeter-wave radar to lightwave signals through the Pockels effect of an EO crystal. Therefore, direct conversion from millimeter-wave radar to lightwave signals can be obtained using the proposed device with simple and compact structures. Furthermore, millimeter-wave losses and distortion are almost negligible since no other planar structures on the substrate except the microstrip patch antennas. The detail device structure, analysis, and experimental results in 40GHz millimeter-wave bands are discussed and reported.

II. Patch-Antennas Feed to Optical Waveguides

Figure 1 shows a structure of the proposed device using microstrip patch antennas feed to optical waveguides in an EO modulator. The proposed device is fabricated on a low-*k* dielectric substrate bonded with an EO crystal such as $LiNbO_3$, $LiTaO_3$, or EO polymer. The microstrip patches are

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inserted between the low-k dielectric substrate and EO crystal. Microstrip patch length (L) as shown by top-view in Fig. 1(b) is set at half a wavelength of the designed millimeter-wave radar signal. Narrow gaps (G) below 10μm are introduced at the center of the antennas. The optical waveguides are fabricated on reverse side of the EO crystal and located on microstrip patches and close to the narrow gaps as shown by cross-sectional view in Fig 1(c). Array of the microstrip patches are arranged with a distance of D. A thin buffer layer is inserted between the EO crystal and microstrip patches. A ground electrode is located on reverse side of the low-k dielectric substrate.

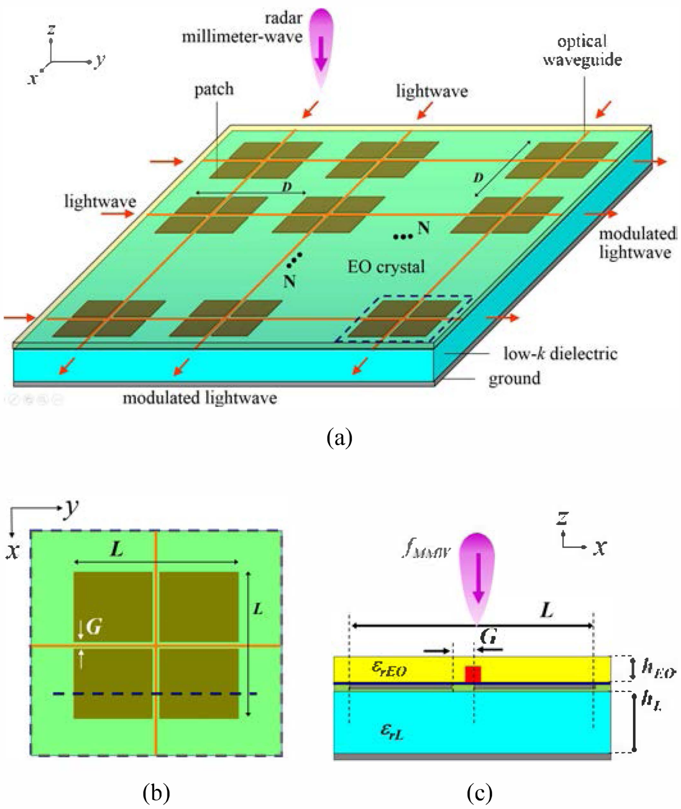

Fig. 1. Structure of microstrip patch antennas feed to optical waveguides in an EO modulator (a) whole view, (b) top view for a single microstrip patch, and (c) cross-sectional view.

When a millimeter-wave radar signal is irradiated to the air space by using an uplink unit, the radiated millimeter-wave radar signal will be reflected by an object. By using the proposed device, the reflected radar signal is detected with the microstrip patch antennas. A standing-wave millimeter-wave current is induced on surface of the microstrip patches. Displacement current is induced across the narrow-gaps due to current flow continuity along the microstrip patches [4,8]. Since the gap width is much narrower compared with microstrip patch length, the characteristic of the microstrip patch antennas in the proposed device are almost no changed compared to the standard microstrip patch antennas with no gaps. Strong millimeter-wave electric field is also induced across the gaps. The induced millimeter-wave electric field can be used for optical modulation through the EO effect. When lighwave propagate into the optical waveguides located on the gaps, electro-optic modulation can be obtained. Based on that, a reflected millimeter-wave radar signal can be received by the microstrip patch antennas and converted directly to lightwave signals through EO modulation.

III. Analysis

In array of microstrip patch antennas feed to optical waveguides, the induced millimeter-wave electric field across the gaps are changed by depending on millimeter-wave incident angles (θ) along x- or y-axes and microstrip patch distance (D). It can be expressed as an equation below for h-th microstrip patches when millimeter-wave radar frequency of f_{MMW},

$$E_{MMW}^{h}(t) = E_0 \sin(2\pi f_{MMW} t + D(h-1)k_m n_0 \sin\theta) \quad (1)$$

where k_m is the wave number of the millimeter-wave , n_0 is the refractive index of the millimeter-wave in air (=1), and D is the distance of the microstrip patches and θ is the millimeter-wave incident angles along x- or y-axes .

When lightwave propagate in the optical waveguides along x- and y-axes as the feeding, the millimeter-wave electric fields along the microstrip patches are collected through EO modulation. As the typical analysis along the optical waveguide in y-axis as following. By taking into account the transit-time ($v_g\, t = y - y`$), the millimeter-wave electric fields observed by a lightwave can be expressed as,

$$E_{MMW}^{h}(y) = E_0 \sin\left(\frac{2\pi f_{MMW}}{v_g} y + D(h-1)k_m n_0 \sin\theta + \zeta\right) \quad (2)$$

where v_g is the group velocity of the lightwave, ζ is an initial phase of the lightwave in the optical waveguides.

The collected millimeter-wave electric fields by lightwave signals in EO modulation along the optical waveguide in y-axis can be formulated as [9]

$$\Delta\phi = \frac{\pi r_{33} n_e^3}{\lambda} \Gamma \sum_{h=1}^{N} \int_0^L E_{MMW}^{h}(y)\, dy \quad (3)$$

where λ is a wavelength of the lightwave propagating in the optical waveguide, r_{33} is the EO coefficient, n_e is the extraordinary refractive index of the substrate, Γ is an overlapping factor between the millimeter-wave and lightwave electric fields, and N is the number of the microstrip patches. The proposed device is operated in electro-optic phase modulation, therefore the sensitivity or conversion efficiency from the millimeter-wave radar to lightwave signals is proportional to the modulation index ($\Delta\phi$) when $\Delta\phi << 1$.

IV. Experiment

The proposed microstrip patch antennas feed to optical waveguides in an EO modulator were calculated. The device parameters for 40GHz millimeter-wave bands were designed with the low-*k* dielectric substrate ($\varepsilon_r = 3.5$; $h_L = 0.13$mm), the EO crystal ($LiNbO_3$; $\varepsilon_r \sim 28$-43; $h_{EO} \sim 70\mu$m), and the microstrip patches ($L = 1.6$mm; $G = 10\mu$m; $N = 5$; $D = 3.6$mm). The optical waveguides were designed using titanium diffusion methods on the $LiNbO_3$ optical crystal with core size of 7 x 2 µm.

Frequency response of the proposed device depends on responses of the microstrip patch antennas and millimeter-wave-lightwave electric field interaction in array structures. By considering that, the frequency response of the designed device can be calculated using equation (3) as shown by solid line in Fig. 2. The calculated frequency response as representative for conversion efficiency or modulation index of the designed device. A radiation pattern of the designed device was also calculated as shown by solid line in Fig. 3.

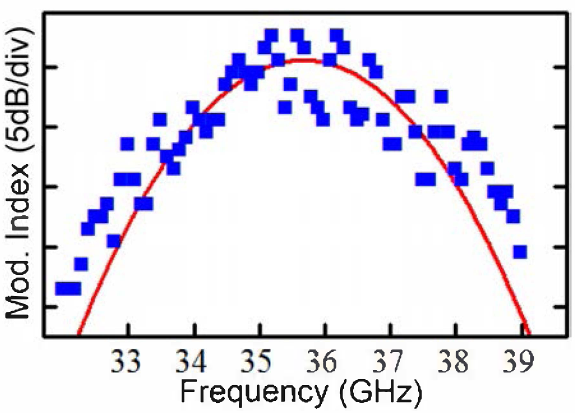

Fig. 2. Frequency responses of the microstrip patch antennas feed to optical waveguides in an EO modulator.

The designed device was fabricated successfully with following steps. Optical waveguides were fabricated on a 250µm-thick *z*-cut $LiNbO_3$ crystal. After that, 0.2µm-thick silicon dioxide film was deposited on the EO crystal. The patches with a 2µm-thick gold film were fabricated on the EO crystal. The optical waveguides were aligned precisely onto one side of the gap edge for effective operation. In the same time, a ground metal was deposited to the bottom surface of a low-*k* dielectric substrate. On the top surface of the low-*k* dielectric substrate, an optical adhesive was deposited. In bonding process, the patches side of the EO crystal was flipped over to the bottom side. Then, they were bonded by exposing ultraviolet light. Finally, the thick EO crystal was polished using a polishing machine with diamond slurry to the designed thickness of about 70µm.

In measurement, the fabricated device was irradiated using millimeter-wave signals and coupled by lightwave from lasers. Lightwave outputs were observed using optical spectrum analyzer. Clear optical sidebands were obtained for indication of EO modulation. The power ratio between optical carrier and sidebands were measured about 38dB by 20mW wireless irradiation power with about 0.5m radiation distance. Therefore, the absolute modulation index of about 0.1 rad m/W can be obtained using the fabricated device. The measured optical sideband power ratio as a function of millimeter-wave frequencies is shown by squared curve in Fig. 2. The measured optical sideband power ratio as a function of millimeter-wave incident angles (radiation pattern) is shown by dotted curve in Fig. 3. We can see that the measurement results are rather matched with the calculation results. The mismatching results might be occurred due to unwanted millimeter-wave reflection signals in measurement setup, substrate resonant mode effect of the EO crystal, or mutual coupling effect of the microstrip patches.

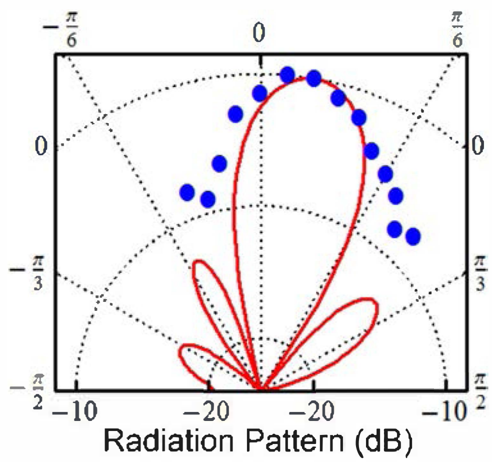

Fig. 3. Radiation patterns of the microstrip patch antennas feed to optical waveguides in an EO modulator.

Based on the results, the proposed microstrip patch antennas feed to optical waveguides are operated basically through EO modulation. The proposed device is promising for downlink of wireless millimeter-wave signals then converting directly to lightwave signals. The proposed device has relatively low modulation efficiency and large bandwidth compare with the integrated structures of antennas and long modulation electrodes [6,7]. In the integrated device structures, antennas, modulation electrodes, and connectors are induced millimeter-wave resonance. Large modulation efficiency can be obtained since they have long modulation electrodes with good matching condition between the metal electrodes. However, the bandwidth becomes narrow since there are many resonant electrodes. Additionally, antennas for high operational frequency in millimeter-wave bands are important for realizing high resolution radars and broadband wireless communication. Precise tuning and low millimeter-wave loss are required for effective operation. We believe that the proposed antennas feed to optical waveguides on EO modulators with ROF technology can be used effectively for eliminating the millimeter-wave drawbacks.

V. Conclusion

Simple and compact microstrip patch antennas feed to optical waveguides in EO modulation were proposed. The basic operations of proposed devise were verified experimentally for 40GHz millimeter-wave bands. 0.1 rad m/W absolute modulation index was obtained using the fabricated device. Direct conversion from wireless millimeter-wave to lightwave signals were obtained with low millimeter-wave losses and distortion. The microstrip patch antennas feed to optical waveguides are promising for operation to high operational frequency in millimeter-wave or terra-hertz bands by adopting ROF technology. The proposed device can be used for high resolution and accuracy millimeter-wave radar systems and other future wireless/ mobile applications.

Efforts for improvement of the antenna gain, modulation efficiency, sensitivity, and operational bandwidth for higher operational frequency in millimeter-wave or terra-hertz bands are still under process in design and development.

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