MICROSTRIP PHASED ARRAY PATCH ANTENNA BASED ON A LIQUID CRYSTAL PHASE SHIFTER FOR OPTICALLY GENERATED RF-SIGNALS

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Abstract
We report on a $1 \times 2$ phased array antenna with optical beamforming network and liquid crystal phase shifter, which allows a continuous microwave phase deviation up to 90°. Experiments in steering the antenna pattern are discussed.

1 Introduction
Electrical feeding and beamforming networks (BFN) for antenna arrays are lossy, bulky and costly components. To overcome these drawbacks, an optical beamforming network (OBFN) [1][2][3] can be used. Additionally, the OBFN can be removed from the antenna array face and located far away in a control station due to the low loss of the signal-transporting optical fibres. We present the concept and measurements of a $1 \times 2$ microstrip phased array patch antenna with an optical beamforming network based on a liquid crystal (LC) phase shifter [4] for microwave signals transported by an optical carrier [4][5][6]. The key component in our OBFN is the LC light valve, the transmittance of which may be controlled electronically. With this OBFN, we vary the electrical phase difference between the antenna elements continuously, and we set independently the amplitude of the electrical signal for each antenna element. This arrangement allows a beam steering of the antenna lobe to different angles.

2 Optical Beamforming Network
2.1 Optical Generation of Microwaves
There are numerous methods to generate microwaves optically, most often based on external or direct modulation of laser diodes, and on optical heterodyning [7]. We use laser diodes with a linewidth of 60 MHz and 530 GHz, emitting at a wavelength of $\lambda_e = 1.55 \mu m$ ($f_c = c/\lambda_e = 193$ THz) and $\lambda_e = 1.3 \mu m$ ($f_c = 229$ THz), respectively, together with an external modulator driven with a microwave signal at 3.6 GHz to generate an amplitude modulated (AM) optical signal as schematically shown in Fig. 1. Modulator-inherent amplitude-phase coupling and other nonlinearities leading to higher harmonics in the detected photocurrent were of no importance. After transmission over a fibre with length $L$, a photodiode (PD) detects the optical power and provides an IF current at the microwave frequency $f_{RF} = c/\lambda_{RF} = f_2 - f_c = 3.6$ GHz. This RF signal is finally amplified and supplied to the patches.

Fig. 1: Optical microwave generation

2.2 Phase Shift by Attenuation
In general, the superposition of two sinusoidal oscillations with normalized amplitudes $A_1$ and $A_2$, and phases $\phi_1$ and $\phi_2$, respectively, is given by

$$ A_1 \sin(\omega t + \phi_1) + A_2 \sin(\omega t + \phi_2) = A \sin(\omega t + \phi). $$

In Eq. (1), $A$ and $\phi$ are amplitude and phase of the superposition. By choosing $\phi_1 = 0$ and $\phi_2 = 90°$, we find

$$ A_1 \sin(\omega t) + A_2 \cos(\omega t) = A \sin(\omega t + \phi) $$

with

$$ A = \sqrt{A_1^2 + A_2^2} \quad (3), \quad \tan(\phi) = A_2/A_1. $$

For $A_1 = 1$, and sweeping $A_2$ from zero to one, the resulting phase $\phi$ will change from 0° to 45° ac-

Fig. 2: Calculated resulting phase shift for two superimposed waves
According to Eq. (4). Letting $A_2 = 1$ and varying $A_1$ from one to zero leads to a phase shift from $45^\circ$ to $90^\circ$ as illustrated in Fig. 2.

To maintain a constant amplitude $A$ for all phases $\phi$, the amplitudes $A_{1,2}$ have to fulfill Eq. (3) for $0 \leq A_1 \leq 1$ and $0 \leq A_2 \leq 1$. Thus, amplitude $A$ and phase $\phi$ may be adjusted independently.

By adding two more sinusoidals with fixed phases $\phi_3 = 180^\circ$, $\phi_4 = 270^\circ$ and normalised amplitudes $A_3$ and $A_4$ in Eq. (1), a phase range of $360^\circ$ can be covered by properly adjusting $A_1$…$A_4$.

### 2.2.1 Structure of the LC Phase Shifter

Figure 3 shows the setup of the liquid crystal phase shifter. The two signals of Eq. (2) with $\phi_1 = 0^\circ$ and $\phi_2 = 90^\circ$ are generated by splitting the modulated light to feed a reference path with $A_1 = 1$ and $\phi_1 = 0^\circ$, and a second path including a $\lambda_{RF}/4$ delay line leading to $\phi_2 = 90^\circ$ for the demodulated RF signal. This second path also contains the liquid crystal to change the amplitude $A_2$ of the signal.

The LC device consists of a polymer-dispersed liquid crystal (PDLC) cell [4] having no polarisation dependence and a large contrast ratio (> 20dB) in the infrared wavelength range. A low frequency (10 kHz) AC voltage ($U$) controls the LC to prevent electrolysis. Scattering behaviour and therefore transmission of the LC depends on the alignment of the LC molecules inside the cell, and is influenced by the magnitude of the AC voltage [4].

![Fig. 3: Structure of the LC phase shifter](image)

The measured normalized transmission $T$ vs. the peak-to-peak voltage of the AC square-wave source is depicted in Fig. 4. The LC cell is opaque for a voltage smaller than 10 V, and fully transparent for a voltage larger than 35 V.

![Fig. 4: Transmission of the LC cell](image)

### 2.2.2 Phase Variation of the RF Signal

Figure 5 shows the measured phase variation at $f_{RF} = 3.6$ GHz as a function of the peak-to-peak voltage $U$. At maximum voltage the normalised transmission of the LC phase shifter is one, and the phase shift corresponds approximately to $45^\circ$. At zero voltage, there is no transmission through the LC cell, and the light is propagating only in the reference path. The resulting phase shift is zero.

![Fig. 5: Phase variation](image)

The setup of Fig. 3 represents an optical interferometer with an actual pathlength difference of about 3 m. Because of thermal and acoustical effects, the pathlength difference, and – as a consequence – the microwave phase changes randomly. Therefore, the more coherent DFB laser (linewidth 60 MHz, coherence length 3.3 m inside a glass fibre) caused phase fluctuations by $\pm 3^\circ$. A less coherent Fabry-Perot laser (linewidth 530 GHz, coherence length 0.4 mm inside a glass fibre) eliminated this problem.

### 2.3 Photoreceiver

The photoreceiver is formed by combining a photodiode and an electrical amplifier (EA). We employ an InGaAs photodiode C30617 to detect the modulated optical signal as depicted in Fig. 1. The ratio of photocurrent $I$ and incident optical power $P$ defines the PD responsivity $R = I / P$ amounting to $R = 0.85$ A/W at $\lambda_c = 1.55$ $\mu$m. The amplifier is an inexpensive Agilent chip (MGA 86576).

Figure 6 shows the magnitudes of the input reflection coefficient ($|S_{11}|/dB$) and of the transmission coefficient ($|S_{21}|/dB$) of the amplifier together with the bias tee for the PD. The input reflection coefficient is lower than $-16$ dB between 3.4 GHz and 3.6 GHz, and the amplifier gain is larger than 23 dB for the same frequency range.

Figure 7 depicts the responsivity of the photoreceiver between 3 and 4 GHz compared to the responsivity of the photodetector without amplifier.
3 Antenna Description

3.1 Single Element

The antenna element is an aperture coupled microstrip patch antenna. Figure 8 shows the structure of a single element. It consists of four dielectric layers (from bottom: Styrodur, RT Duroid 5880, Rohacell, and capton foil). The middle layer (RT duroid 5880, \( d_r = 0.508 \) mm) is metallized on its upper side. This metallization acts simultaneously as a ground plane for the quadratic metal patch situated on top of the uppermost layer (capton foil), and for the 50 \( \Omega \) microstrip line on the lower side of the middle layer which excites the patch through the slot in the ground plane. The patch has lateral dimensions of \( l_p = 26.5 \) mm and operates as a planar open resonator in the fundamental mode. Depending on the thickness of the low permittivity (\( \varepsilon_c = 1.25 \)) compound material formed by Rohacell \( (d_r = 11 \) mm) and the capton foil, the fringing fields at the patch edges parallel to the \( x \)-axis carry a considerable amount of energy, and the patch radiates into free space with a co-polarised electric field vector lying in the \( y-z \)-plane. The size of the slot \( (l_s = 23 \) mm, \( w_s = 2.85 \) mm) determines the coupling between the feeding microstrip line and the patch, and therefore influences the antenna input impedance. Its imaginary part has been compensated by using a stub of 3.9 mm, which extends the microstrip line beyond the centre of the coupling slot. At the lower side of the bottom-most dielectric layer serving as a spacer, a metallic reflector plane prevents backward radiation from the coupling aperture and the microstrip line.

We designed the patch antenna by using the programme package Ensemble Version 8 by Ansoft. In Fig. 9, the measured modulus of the input reflection coefficient \(|S_{11}|/\text{dB} = 20\log(|S_{11}|)\) for a single element in the frequency range \( 3...4 \) GHz is shown. The 14-dB bandwidth is 750 MHz. For a 56-MHz bandwidth centred at 3.5 GHz, the input reflection coefficient is below \(-25 \) dB.

Figure 10 displays the relative co-polarised electric field component \( E_\phi \) (perpendicular to the \( x-z \)-plane) and the relative cross-polarised electric field component \( E_\theta \) (parallel to the \( x-z \)-plane in Fig. 8) as a function of the angle \( \theta \) measured from the \( z \)-axis. The difference between co- and cross-polarisation is larger than 20 dB. For the \( 1 \times 2 \) array (Fig. 11), the inter-element centre-to-centre spacing was \( d = 0.52 \lambda_s \), where \( \lambda_s = 76.7 \) mm is the substrate wavelength of the compound material formed by Rohacell and the capton foil as shown in Fig. 8. In Fig. 11 the whole antenna structure is shown. Different lines have been used to indicate the position of the elements in the multilayered structure as given in Fig. 8.
4 Measurement of the Complete Antenna System

Figure 12 illustrates the measurement setup. A CW laser diode (LD) is followed by a Mach-Zehnder-Modulator (MZM), which modulates the optical carrier with a sinusoidal RF signal of frequency $f_{RF} = 3.6$ GHz. An Erbium-doped fibre amplifier (EDFA) increases the optical power. The modulated optical intensity is fed via an optical power divider (OPD) to two paths ($I_1, I_2$) for the two antenna elements. In order to vary the RF phase of one antenna element, the LC phase shifter controls path $I_1$. Thus, the radiation pattern can be steered to the desired angle. Figure 13 shows the measured and calculated far-field pattern of the antenna array at different viewing angles $\theta$.

For a scan at an radiation angle offset $\delta \theta = 12^\circ$ or $16^\circ$, the phase difference between the antenna elements $\delta \phi$ was $38^\circ$ or $48^\circ$, respectively, as can be estimated roughly by

$$\sin(\delta \theta) = \frac{\lambda_{RF} \delta \phi}{2\pi d}.$$ 

Measurements and calculations are in good agreement.

5 Conclusion

A basic $1 \times 2$ phased array microstrip patch antenna with an optical feeding network based on a liquid crystal phase shifter for optically generated microwave signals is presented. The characteristics of the different parts of the system have been measured. The patterns of the antenna array for different viewing angles have been presented.

References