Coplanar Phased Array Antenna with Optical Feeder and Photonic Bandgap Structure

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Abstract: *A novel coplanar broadband dipole phased array sending antenna with optical feeder network and photonic bandgap structure has been developed. Hybridly integrated opto-electronic receivers and high-gain MMIC power amplifiers detect the modulated optical input power and deliver a 20-GHz microwave signal to the antenna elements. A planar photonic bandgap structure surrounding each dipole and its electric feeder line suppresses parallel plate modes of the conductor-backed substrate. The relative antenna bandwidth could be tripled from 7.5 % to 22 %.*

Introduction

RF feeders and electronic beamforming networks (BFN) for phased array antennas are bulky and costly. We designed a sending-mode 20-GHz ($\lambda = 15$ mm) conductor-backed coplanar λ-dipole slot antenna array with an *optical* BFN (OBFN) consisting of true time delay (TTD) single-mode fibre feeders and opto-electronic converters. Besides the conceptual simplicity of removing the BFN from the array face, such a TTD feeder avoids a frequency dependent beam squint /1/–/3/. By switching the time delays of the OBFN adaptively, an intelligent space-diversity antenna may be designed, where each beam tracks possible movements of a mobile subscriber.

To overcome the typical 7-% bandwidth limitations of dipole slot antennas, we developed a planar photonic bandgap (PBG) structure to suppress parasitic parallel plate modes, thereby increasing the bandwidth to 22 %.

We give design details of the antenna structure, and we present preliminary experimental results.

PBG antenna design

Fig. 1 shows the coplanar waveguide (CPW) antenna structure etched on a 104 mm × 81 mm RT Duroid 5880 substrate with a thickness of 1.57 mm, an effective refractive index of $n_e \approx 1.5$, and a medium wavelength of $\lambda_e = \lambda / n_e \approx 10$ mm. The radiating slot length, slot width, and the separation of the dipole elements are $\lambda_e/2 = 5$ mm, 1 mm, and $1.7 \times \lambda_e = 17$ mm, respectively. The slot width of the 50-Ω coplanar feeding line (odd mode) decreases from 100 µm near the dipoles to 15 µm in the tapered region near the microwave amplifiers HP HMMC-5040 (A). The photoreceiver (PR), an opto-electronic integrated circuit (OEIC) /4/, is biased at its RF output by a DC voltage. The bias-T consists of a 150-µm line leading to the PR RF output, and a blocking interdigital capacitor in front of amplifier A.

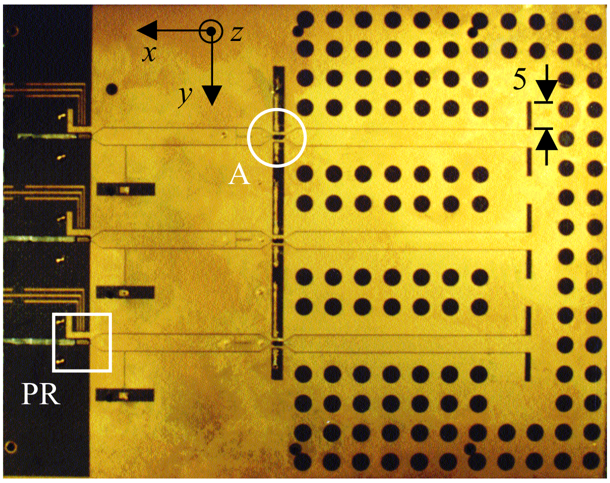

Fig. 1. PBG antenna with integrated photoreceiver OEIC (PR) /4/ and MMIC amplifiers (A)

Backward radiation is avoided by a back metallization on a Rohacell foam spacer (refractive index 1.025) with a thickness of

5 mm, a structure known as a conductor-backed (CB) CPW. Waveguides and radiating slots are surrounded by circular apertures etched out of the top metal layer, having a diameter of $0.2 \times \lambda = 0.3 \times \lambda_e = 3$ mm, and thus operating below their resonance frequency. Periodic apertures of the same size are also etched out of the back metallization. The spatial period of the PBG structure equals the length $\lambda/3 = \lambda_e/2 = 5$ mm of the radiating slots. Any radiation from the PBG apertures is therefore effectively cancelled by destructive interference. Uniplanar two-dimensional periodic PBG structures gain presently much interest /5/. Application examples with very complicated PBG structures for suppressing parasitic parallel plate modes in CB-CPW were recently presented by /6/.

Simplified antenna

Using a simplified version of the antenna structure in Fig. 1 without amplifier A and without PBG structure, we checked the basic performance as a first step. In Fig. 2, the right-hand side shows the dipoles with CPW feeders dimensioned as in Fig. 1. An enlarged view of the PR region, marked by a rectan-

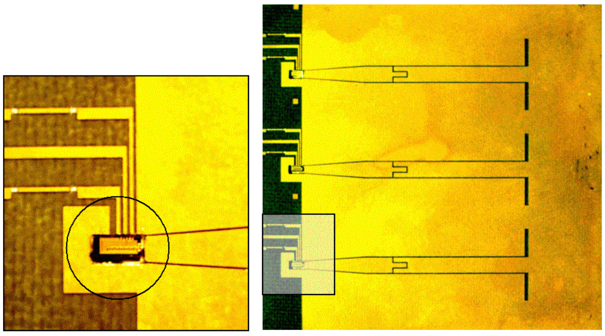

Fig. 2. Simplified antenna structure of Fig. 1 without amplifier A and PBG structure. An enlarged view of the PR region is seen on the left-hand side (encircled)

gular, is displayed on the left-hand side. The photoreceiver PR /4/ is grown on a semi-insulating GaAs substrate with chip dimensions 2.5 mm × 1 mm, Fig. 3. It includes a pin photodiode (PD) with a circular light-sensitive area of 10 µm diameter, and a six-stage HEMT distributed amplifier with a total gain of 14 dB. The 0.15-µm gate-length pseudomorphic HEMT with a 12 nm thick $In_{0.25}Ga_{0.75}As$ channel have an extrinsic transconductance $g_m = 745$ mS/mm, a current-gain cut-off frequency $f_T = 90$ GHz, and a maxi-

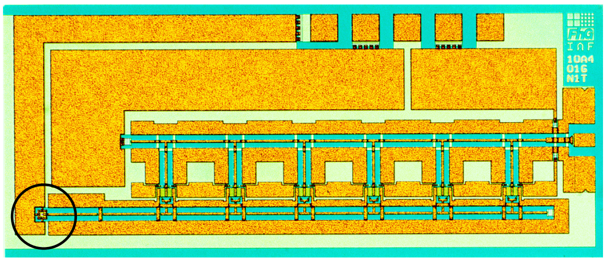

Fig. 3 Photoreceiver /4/ (PR, see Fig. 2) with a four-stage distributed amplifier (2.5 mm × 1.0 mm); surface-illuminated pin photodiode PD marked by circle

mum oscillation frequency $f_{\max} = 150$ GHz. Each stage of the distributed amplifier consists of a cascoded pair of HEMT with 90 µm gate-width, embedded in 70 Ω coplanar transmission lines. To achieve a high bandwidth, the input impedance is kept as low as 30 Ω. At $\lambda = 1.55$ µm, the responsivity, dark current, and capacitance of the PD are 0.34 A/W, 15 nA and 109 fF at −2 V bias, respectively. The entire pin-HEMT PR has a transimpedance of 146 Ω corresponding to an O/E conversion factor of 50 V/W, and a bandwidth suitable for NRZ data transmission up to 40 Gbit/s.

We measured the antenna input reflection coefficient $|S_{11}|/\mathrm{dB} = 20\lg|S_{11}|$ of a single antenna element with a provisional electric

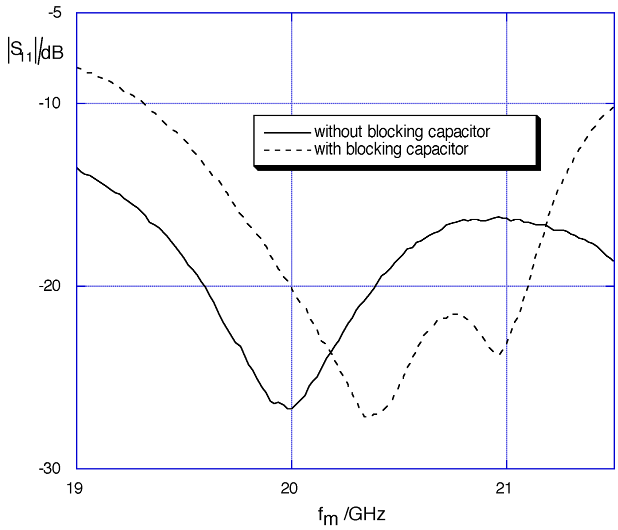

Fig. 4. Modulus of input reflection coefficient $|S_{11}|$ for a single antenna element of Fig. 2

connector as a function of the RF frequency f_m without (——) and with (– – –) the interdigital blocking capacitor, Fig. 4. The 14-dB bandwidth in the second case amounts to 7.5 %.

With a set-up according to Fig. 5 we investigated the opto-electronic behaviour. A CW

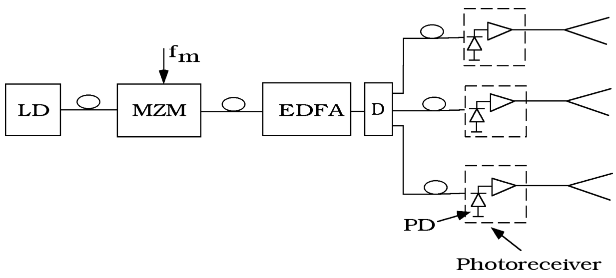

Fig. 5. Opto-electronic measurement setup

DFB laserdiode (LD) is followed by a Mach-Zehnder-Modulator (MZM), which modulates the optical carrier with a sinusoidal RF signal of frequency $f_m = 20$ GHz. An Erbium-doped fibre amplifier (EDFA) increases the optical power. The modulated light is symmetrically distributed by a 1:3 fibre-optical power divider (D), and finally coupled via a standard single-mode fibre to the top-illuminated PD of each of the PR.

We measured the radiation pattern of a single element in the H-plane (*y*-*z*-plane in Fig. 1), both for an all-electrical excitation of the antenna, and for an opto-electric feeder as described above. The differences in both radiation patterns Fig. 6 stem from the masking of the non-excited antenna elements for preventing radiation coupling during the single-element measurements.

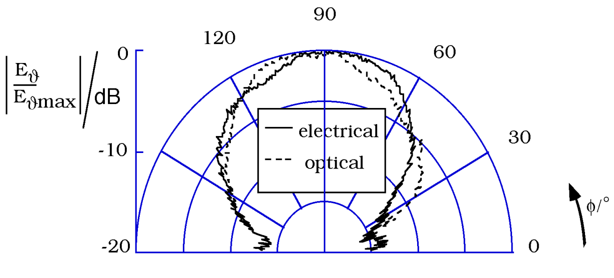

Fig. 6. Radiation pattern of a single antenna element in the structure Fig. 2 at $f_m = 20$ GHz: Relative magnitude of the electric field E_ϑ in the direction of the *x*-axis of Fig. 1, measured as a function of angle ϕ in the H-plane (*y*-*z*-plane in Fig. 1)

PBG single element antenna

The 7-% bandwidth limitation of the simplified antenna Fig. 2 is caused by the excitation of the parasitic parallel plate mode of the CB-CPW; therefore, we designed a PBG structure to prevent the propagation of this mode. With initial guidelines as given in the text following Fig. 1, we computed the RF input reflection factor $S_{11}(f)$ at the output port of amplifier A in Fig. 1 for a single antenna element, and varied the PBG design by trial and error. We employed the software package Ensemble Version 6.0 (Ansoft). The calculation time using a 450-MHz PIII processor with 512 MB RAM amounted to 36 h for 21 different frequencies. Measurement results are to be seen in Fig. 7. The bandwidth of our PBG antenna tripled from 7.5 % to 22 % (4.4 GHz).

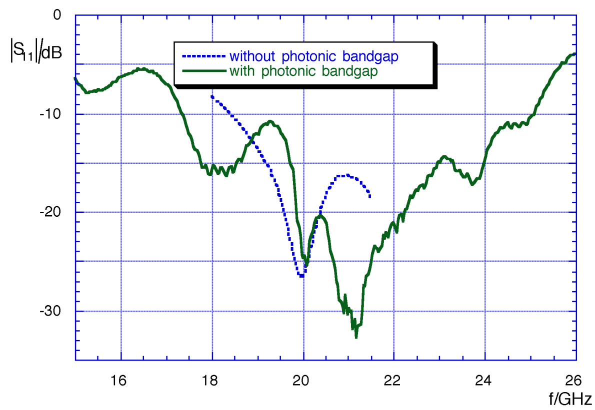

Fig. 7. Modulus of input reflection coefficient $|S_{11}|$ for a single PBG antenna element (——) after amplifier A in Fig. 1, and for an equivalent element without PBG structure (see Fig. 2), copied from Fig. 4 (– – –)

With the same electric feeder as before, we measured the radiation pattern. Fig. 8 displays

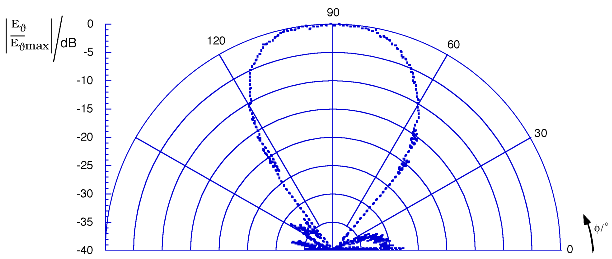

Fig. 8. Radiation pattern of a single PBG antenna element in the structure Fig. 1 at $f_m = 20$ GHz. Notation as in Fig. 6

the magnitude of the electric field component $20\lg(E_\vartheta/E_{\vartheta\max})$ in the direction of the *x*-axis of Fig. 1, measured as a function of angle ϕ in the H-plane (*y*-*z*-plane in Fig. 1). The full width 3-dB angular breadth amounts to $\Delta\phi^{(1)}_{3\,\mathrm{dB}} = 40°$.

PBG antenna array

For checking the PBG array layout, we designed a provisional *electric* beamforming network to feed the three antenna elements of Fig. 1, again at the points, where the outputs of amplifiers A are located. The corresponding pattern is seen in Fig. 9, and shows a full width 3-dB angular breadth of $\Delta\phi^{(3)}{}_{3\,\mathrm{dB}} = 0.4 \times \Delta\phi^{(1)}{}_{3\,\mathrm{dB}} = 16°$. The sidelobe suppression is

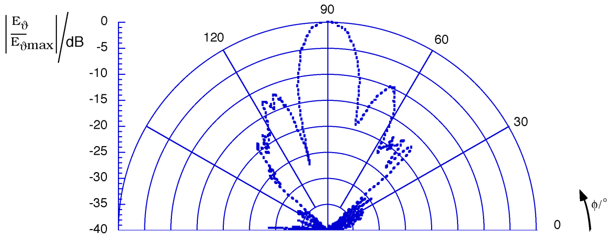

Fig. 9. Radiation pattern of a PBG antenna array in the structure Fig. 1 at f_m = 20 GHz. Notation as in Fig. 6

slightly below the usual 12–15 dB; however, because of memory size and computing time restrictions, we did not yet optimise the layout.

Further work

External optical modulators are expensive components, so we propose a direct intensity modulation (IM) via the injection current of the LD. Associated with injection current changes, we see – besides AM sidebands – also a large number of frequency modulation sidebands (chirp) in the optical spectrum. Because a PD cannot detect FM, a dispersive optical fibre or a fibre Bragg grating acts as a FM-AM converter, so that the receiving PD can detect the *k*th harmonics of the LD modulation signal f_m /7/.

To boost the electric output power of the photoreceiver PR, a microwave amplifier A (HP HMMC-5040, 1.7 mm × 0.76 mm, 20–44 GHz) with 22 dB gain was provided in Fig. 1, but not activated yet. With an optical input power of 1 mW, the PR delivers 25 µW corresponding to −16 dBm at the input port of A. The antenna efficiency is in the order of 50 % (3 dB loss), so about 3 dBm (2 mW) of radiated power are to be expected. A 2.6-fold increase in PD efficiency to 0.9 A/W for an improved PR design gives a gain of 4 dB, leading to a radiated power of 7 dBm (5 mW) for each element. The OEIC and the RF components allow a simple scaling to a design frequency near 40 GHz.

Conclusion

We designed a coplanar phased array antenna with optical feeder and photonic bandgap structure, and investigated the system using an external light modulator. At f_m = 20 GHz we measured a large relative bandwidth of 22 % (4.4 GHz). The radiated power is expected to be 7 dBm (5 mW) per element. The components allow a design scaling to $f_m \approx 40$ GHz.

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