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Optoelectronics Enabled Dense Patch Antenna Array for Future 5G Cellular Applications

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Abstract *Interconnection between densely-spaced antenna array elements to separated signal processors is a challenge in practical systems of future 5G applications. We present an interconnect concept based on optoelectronic link and a proof-of-concept experiment demonstrates successful 6-Gbps 64-QAM data transmission.*

Introduction

Demands on high data transfer rate over wireless systems increase every year. Smart millimeter-wave (mm-wave) wireless systems are inevitable for very high data rate communication such as 5-10 Gbps data transfer capacity in 5G communication systems and even higher capacity in future smart systems¹. A key enabling technology in 5G mm-wave (at 24-52 GHz bands) systems is a compact antenna with radiation elements independently connected to a massive number of independent transceivers, thereby forming a massive multiple input multiple output (MIMO) array².

Several compact patch array antenna structures have been proposed to be used in massive MIMO systems³⁻⁵. At mm-wave frequencies, antenna element sizes are typical 1-3 mm with less than 10 mm spacing between each elements. It is a challenging task to provide high frequency signal routing between these antenna elements and their respective transceiver circuits. Already at 3.7 GHz, the patch antenna to transceiver electronic interconnect is a challenge using RF-cables². Heat dissipation is another major issue that prevents such system to be used in practical scenarios.

To resolve this challenge, we propose the use of ultra-low power VCSEL arrays to relay 5G mm-wave signals from antenna elements to separate transceivers using a multicore multimode fiber. There are two main advantages: firstly, the VCSEL together with the driver is less than 1x1 mm²/channel, which easily fits between antenna elements; secondly, the VCSEL and driver consume much less power (~300mW/channel) compared to integrated transceivers², making it easier to meet heat dissipation requirements in massive MIMO systems.

Optoelectronics-antenna integration has been demonstrated below 6 GHz using VCSELs⁶. However, not much work has been done at frequencies higher than VCSEL's 3-dB cut-off frequency. A 22 Mbps transmission at 40 GHz was demonstrated using a mode-locked laser, but only 4 MHz RF bandwidth was available with such a laser⁷. In this work, we managed to obtain up to 6 Gbps 64-QAM data transmission using a 1.75 GHz bandwidth at several bands between 24-28 GHz using an in-house developed VCSEL array⁸ and a customized wideband driving amplifier⁹. Furthermore, high integration level is addressed by a compact packaging concept co-designed with antenna.

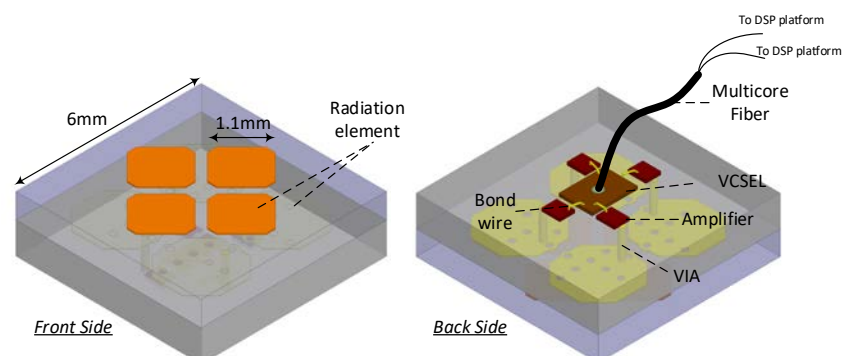


Fig. 1: Proposed dense antenna array enabled by a multicore fiber and VCSEL array interconnect solution

Proposed dense antenna array enabled by optoelectronic interconnection

In a dense ultra-wideband (UWB) antenna array, the spacing between radiation elements can be less than $\lambda/4$ at the lower end of the frequency band (i.e. 2.2 mm at 30 GHz). This leads to packaging challenges when each radiation element is connected to an individual transceiver chip⁴ (normally larger than $5 \times 5 \text{ mm}^2$). We instead propose an optoelectronics based solution as shown in Fig. 1. A basic capped bowtie antenna⁵ unit cell that contains 2×2 elements is given as example. The front side and the back side of the antenna are shown in the figure where the optoelectronics is integrated on the back side as illustrated. Each path element is $1.1 \times 1.1 \text{ mm}^2$ and they are 2 mm apart from each other. Via holes bring the signals from antenna elements to the backside through the substrate. On the backside, the signals from the vias are fed to variable gain amplifier (VGA) chips ($0.6 \times 0.55 \text{ mm}^2$ each) using wire bonding. The VGA chip also functions as a driver for the VCSEL array (with size $0.72 \times 0.42 \text{ mm}^2$ for the 6-channel array⁸). Using the VCSEL array, signals from the different antenna elements are sent to different receiver processors using a multimode fiber.

A photo of the $0.25 \mu\text{m}$ InP DHBT based VGA chip⁹ is shown in Fig. 2 together with its measured small signal frequency response. The gain of the VGA can be adjusted with the bias voltage up to 30 dB at 30 GHz, thus the VCSEL is driven at a constant power level regardless of the received power from the antenna element. A photo of the VCSEL array is shown in Fig. 3 together with its measured small signal modulation response⁸. It can be seen that at 12 mA bias, the VCSEL contributes 10 dB loss at 30 GHz.

Experimental setup and concept verification

To verify the proposed packaging and interconnect concept, the VGA is used as a driver for one of the 850 nm VCSELs in the array to transmit the mm-wave signal over a multimode optical fiber. A proof-of-concept data

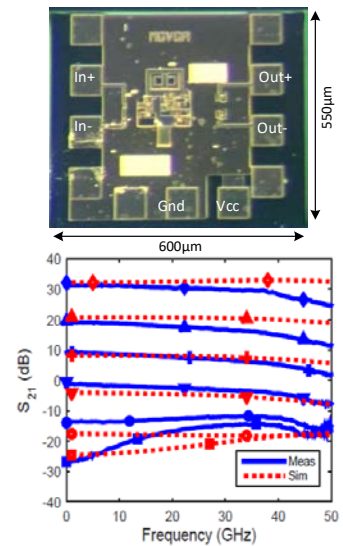


Fig. 2: Photo of the InP DHBT variable gain amplifier and its simulated & measured frequency response at different control voltages between 2.3-2.5 V [9].

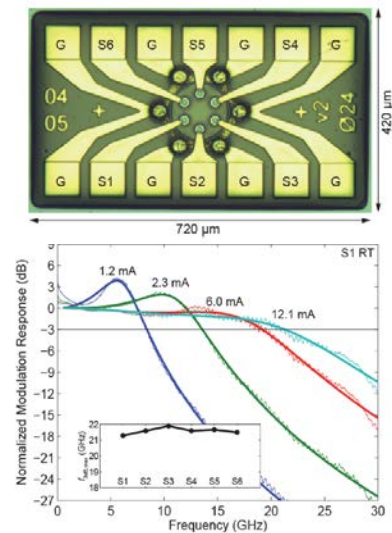


Fig. 3: Photo of the six-channel VCSEL array and its measured small signal modulation response [8].

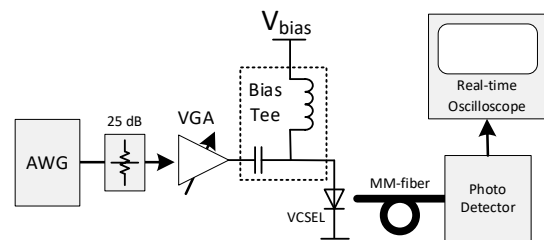


Fig. 4: Proof-of-concept experimental setup.

transmission test is made at 24-28 GHz with different QAM modulated. The experimental setup is described in Fig. 4.

An arbitrary waveform generator (Keysight M8195A 65GSa/s) generates differential QAM modulated output signals at 24-28 GHz. The output of the AWG is attenuated by 25 dB to emulate the free space loss over air transmission. A VGA amplifies the input signal and drives the VCSEL. A bias-tee is used to connect the VGA and the VCSEL while providing bias current to the VCSEL. The output from the VCSEL is coupled to a 1-meter multimode fiber and a commercial photodetector (1484-A-50) converts the optical signal back to an electrical signal. A real-time oscilloscope (LeCroy LabMaster 10-100Zi) is used to digitize the signal and perform demodulation. The error-vector-magnitude (EVM) of the modulated signal is analyzed to verify the feasibility of RF signal transmission.

Experimental results and discussion

The received 1 Gbaud constellation diagrams at 24 GHz are plotted in Fig. 5. In the left column, the signals are recorded with the AWG output directly connected to the oscilloscope. Therefore, it can be used as a reference. In the right column, the signals are recorded after passing through the optoelectronic link. Signal distortion and extra noise are observed in comparison with the diagrams on the left. In this configuration, 16-QAM, 32-QAM and 64-QAM provide effective data rates of 4, 5 and 6 Gbps, respectively. Transmission of 500 Mbaud 16-QAM signals at 24-28 GHz was also tested. The received constellations, EVMs and BERs are presented in Fig. 6. At a higher mm-wave carrier frequency, the VCSEL and photodetector introduce more loss and therefore the signal-to-noise ratio (SNR) is reduced. However, noise cancellation based on massive MIMO configuration can be used to compensate the SNR reduction. Nonlinear distortion was not observed when increasing the carrier frequency.

To the best of authors' knowledge, this is highest data rate QAM data transmission ever demonstrated above 20 GHz over VCSEL link and this is first attempt of using VCSEL array for patch antenna array interconnect.

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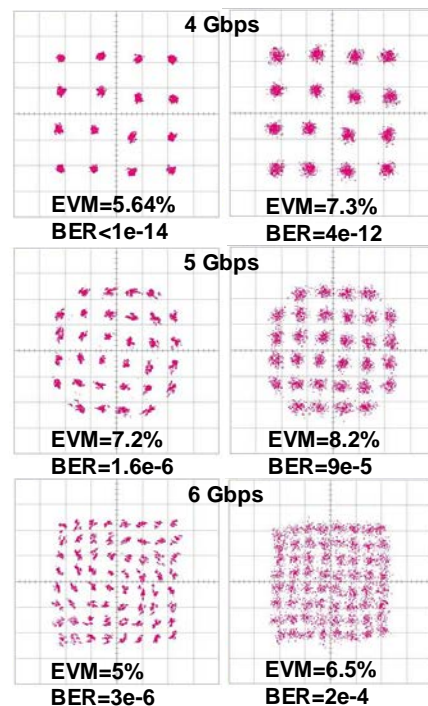


Fig. 5: Measured constellation diagrams at the AWG output (left) and after the optical link (right). All constellations are at 1 Gbaud symbol rate.

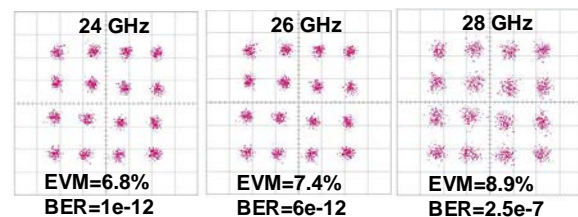


Fig. 6: Measured constellation diagrams after the optical link at 500 Mbaud 16QAM (2 Gbps) with 24, 26 and 28 GHz mm-wave frequencies.

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