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A Transmit/Receive Active Antenna with Fast Low-Power Optical Switching

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Abstract—
An X-band active antenna element for half-duplex transmit/receive (T/R) applications with efficient optical switching is presented. The antenna element is designed to be a unit cell of a quasi-optical array with fast switching between T and R and with built- in phase-shifterless beamforming. The measured performance of the active element is 14dB gain contributed by the power amplifier (PA) in transmission, 16dB gain contributed by the LNA in reception, with 30dB isolation between T and R. The switching is accomplished with only 1μW of optical power for 1.7μs switching time, and a rise time of 2ns at 10GHz with 7mW of optical power. The design, implementation and measured performance of the optically-controlled transmit/receive circuit are presented here in detail.

I. Introduction and Motivation

With the increasing complexity of modern communication environments, antenna arrays with a number of simultaneous beams are of interest. One possible realization of multiple-beam arrays are active antenna array lenses (AAAL) with spatial feeds [1], [2]. Some advantages of this architecture are: phase-shifterless beamforming; lower feed losses than those associated with cooperate feeds for large number of array elements; improved dynamic range in reception; high EIRPs in transmission; and graceful degradation in both transmit and receive modes [3], [4]. Transmit/receive (T/R) AAALs can operate in full-duplex or half-duplex modes. Full-duplex operation (simultaneous transmission and reception) requires separate array elements, selective duplexers (filters), or the use of circulators to route transmit and receive signals through the appropriate amplifiers. Half-duplex operation uses microwave SPDT switches to route the transmitted and received signals, and is the topic of this paper.

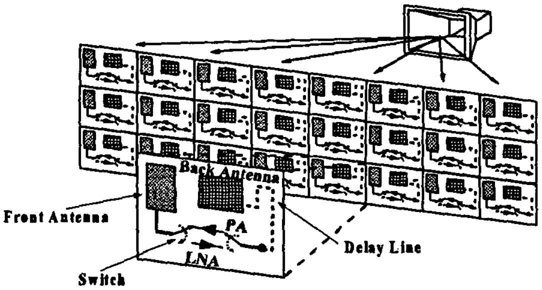

Fig. 1. Sketch of a cyllindrical T/R active antenna lens array with half-duplex operation.

Figure 1 shows an example of a cylindrical active lens with half-duplex operation. Each array element contains two antennas (shown here as patch antennas on each side of the lens), a power amplifier (PA), a low noise amplifier (LNA) and two SPDT switches. In transmission mode, the patch antennas on the feed side receive signals from one or more feed antennas (represented by horns in the figure) located along the focal arc of the lens. In

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each element, the signal is delayed in relation to their position on the lens: unit cells in the center have longer delays than edge elements, in analogy to an optical lens being thicker in the center than on the edges. The switches then route the signals through PAs before re-transmitting a coherent combination of all the element powers. In reception, the signals are routed through LNAs in each element. Different positions of a feed along the focal arc correspond to different main beam angles, since the lens is angle preserving. In addition, for linear amplifiers in the lens, several feeds can be used simultaneously for beamforming.

In half-duplex T/R lens arrays demonstrated to date, the switches are controlled in parallel and the bias and control lines contain capacitors that suppress bias-line oscillations [3], [4]. As a result, the rise and fall times of the array when it is switched between T and R increase with the number of array elements. Individual control of each element, however, increases the complexity of the control lines and the cost. A possible solution, explored in this paper, is to optically control switches in each unit cell of an array [5]. In this case, the switching speed of the array is independent of its size and equal to the switching speed of each element. Further, optical fibers that carry the switching control signals do not affect the microwave radiation.

Previously demonstrated optically controlled microwave switches use optical power to generate carriers in microwave pin diodes [6], [7], [8]. The disadvantage to this technique is the fact that the insertion loss (IL) and isolation of the switch depend strongly on optical power, and as much as 40mW of optical power can be required to achieve an IL of 1.2dB and an isolation of 30dB [8]. The optically controlled microwave switch presented in this paper uses a small amount of optical power to control the bias of chip pin diodes. The advantage of this technique is that only the switching speed (rise and fall times) is a function of incident optical power, while the IL and isolation are independent of it.

II. DESIGN OF OPTICALLY-CONTROLLED MICROWAVE T/R SWITCH

Figure 2 shows the schematic of the array element used in this work. 10-GHz patch antennas with a common ground plane and vias between feed and radiating sides of the array are used to improve isolation between in the input and output signals of the amplifiers. Off-the-shelf MMIC amplifiers are used for the PA (HP HMMC-5618, 14dB gain from 6 to 20GHz with 18dBm power at the 1-dB compression point) and LNA (United Monolithic Semiconductor CHA2063, 16dB gain from 8 to 13GHz with a noise figure of 2dB). MA/Comm MA4GP032 *pin* diodes, with a 3Ω on- resistance at 3mA and 0.12pF capacitance in the off state are used for the microwave switch. 25μm diameter and 0.5mm long gold bond wires are used as 1nH inductors in a T network with the pin diodes to improve performance by reactance cancellation. The resulting single-pole single throw (SPST) switch has a measured IL of 0.75dB and an isolation of 20dB from 6 to 13GHz.

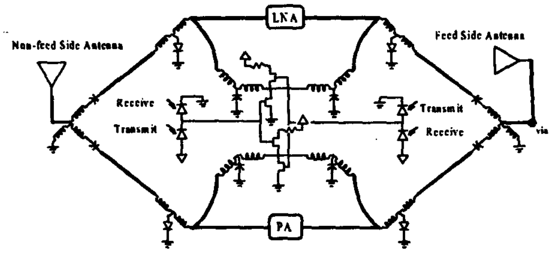

Fig. 2. Diagram of the active antenna element described in this paper.

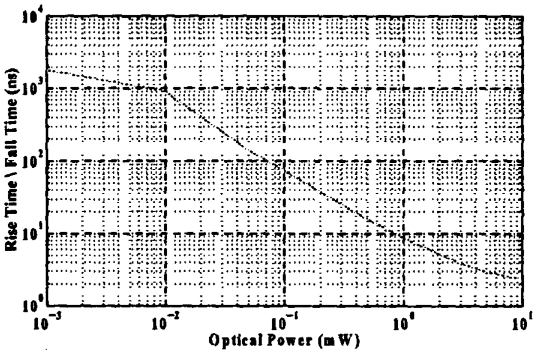

Fig. 3. SPICE simulation of rise and fall times of the optically- controlled microwave switch as a function of optical power per photodiode.

Compact high-pass (HPF) and low-pass filters

(LPF) are needed to separate the bias/control and RF signals. In the unit cell, a second order HPF isolates the bias control for each side of the SPDT switch. This filter exhibits at least 20dB rejection below 1GHz and 0.1dB loss at 10GHz, and is implemented with a 2nH shunt bond wire and a 1pF chip capacitor at 10GHz. An additional bond wire is needed to connect the chip capacitor to the microstrip line and is designed to be resonant with the capacitor at 10GHz. A third order LPF biases the *pin* diodes with 27dB rejection (0.1dB reflection) of the 10GHz RF carrier. This LPF is implemented with 0.85nH bond wires and 3pF capacitors. The low impedance of this combination is transformed into a high impedance with a $\lambda g/4$ long microstrip line causing a 0.1dB reflection at the bias line junction.

The optically-controlled bias to the *pin* diodes is implemented with a HP ATF26836 general purpose MESFET (9dB gain, f_T=16GHz) and Fermionics FD80S3 1300nm photo-diodes (PD) (with 0.95A/W responsivity and an active area with a 80μm diameter). The MESFETs are used to sink and source the current of the pin diodes, allowing for small on/off response times. Push-pull PD's controls the gate bias point for the MESFETs. The switch is supplied from the MMIC's bias line through a current limiting resistor, eliminating the need for extra bias lines.

The MESFET gate capacitance and PD on-resistance dominate the rise and fall times of the bias control circuit. Figure 3 shows SPICE simulation results for rise and fall time as a function of optical power per PD. It can be seen that the fastest expected response for the switch is 2.6ns at 7mW per PD, and is determined by the RC time constant resulting from the pin diode junction capacitance and the current- limiting resistor. For only 1μW of incident optical power, the switch rise (and fall) time is approximately 2000ns.

III. Performance pf Active T/R Antenna Element

Figure 4 shows the layout of the active antenna element. An optical mount (Figure 5) aligns the optical fibers to the PD with an accuracy of 200μm, limited by the packaging of the commercial PD.

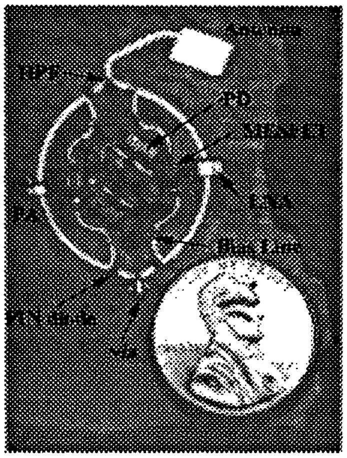

Fig. 4. Photograph of the active antenna element without the fiber optic mount.

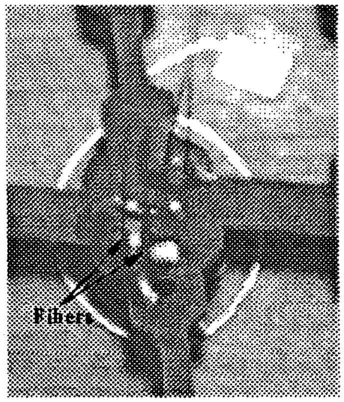

Fig. 5. Photograph of the active antenna element with the fiber optic mount.

The measured SPDT switch in the active antenna element has an IL of 0.31dB and an isolation of 36dB over a 2.5GHz 2:1 VSWR bandwidth (8.36 to 10.8GHz).

For testing the optical switching performance, variable length complimentary optical pulses with fast edges are needed. Two 3GHz Uni- Phase intensity electro-optic (EO) modulators are used to generate the optical pulses. They are controlled by a function generator and inverting/non-inverting op-amps and two Veritect EO drivers. An Ortel

10mW 1300nm fiber-pigtailed laser diode is the optical source. The resulting optical pulse has a pulse width varying from 25ns to 7000ns with constant rise (fall) time of about 1ns. The optical pulses are incident on the PDs through free-space coupling from multimode fibers placed about 0.5mm above the PD chip. The loss resulting from free space coupling of the optical power limited the testing range of the switch (3 to 15μW were only available). The measured results agree with simulated values and fall within the simulated bounds. The bounds result from uncertainty in optical power delivered to the PDs, which in our setup varied by +1.7dB and -2.7dB.

Based on path loss measurements calibrated to an aperture the size of a unit cell (0.75λ x 1λ). The unit cell has a gain of 3dB and 1dB for receive and transmit modes, respectively. These gain numbers are estimates calculated to within 2dB accuracy and based on the Friis transmission formula and assuming values for via loss, antenna efficiency and switch insertion loss. The gain contributed by the amplifiers is calculated from measurements to be 14dB from the PA and 16dB from the LNA, consistent with device specifications. An isolation of 30dB was measured for cases when: the active antenna was in receive mode while transmitting; the active antenna was in transmit mode while receiving; as well as when the active antenna was in the off state. These measurements are limited by edge diffraction and feed cross- polarization quality.

Based on the above measurements, we are designing a 6λ by 3λ cyllindrical active lens array with a focal distance to diameter (F/D) ratio of 1. The directivity of this active lens is 19.8dB with a 10-degree half-power beamwidth in the lensing (focusing) plane.

IV. CONCLUSION

In this paper, we describe the design and demonstration of a fast optically controlled transmit/receive active antenna intended for integration into an active spatially fed lens array. The active element is designed using off-the-shelf components not optimized for speed or low power. The rise time and fall time of the microwave switch is determined by the optical power, allowing the switch to be tailored to each application. The fast rise time/fall time of 2.6ns is not required for switching between transmit/receive modes in most current applications, and would also require relatively high optical power levels for a larger number of switches, but microsecond switching speed can be accomplished with quite low optical power. Some applications, however, such as phase shifters in phased array or polarization switching in multipath environments could benefit from fast optically controlled switches. We are currently improving the optical feed to reduce coupling loss from the optical fibers to the photodetectors.

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