EFFICIENT OPTICAL CONTROL OF MICROWAVE CIRCUITS, ANTENNAS AND ARRAYS

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Abstract – **We present an overview of work at the University of Colorado in the area of optical control of microwave circuits, antennas and active antenna arrays. In specific, we present X-band examples of two types of optically controlled microwave components: those where the optical device is used as a microwave component; and those where a standard optical component is combined with standard microwave components. The former is a slot antenna controlled with a PD in the feedline; and the latter example is that of a photodiode that controls the bias to a microwave SPDT switch. This switch is integrated with a transmit/receive (T/R) active antenna, which is then used as an element of a quasi-optical T/R array.**

I. INTRODUCTION AND MOTIVATION

The goal of the work overviewed in this paper is to demonstrate the feasibility of efficient optical control of microwave circuits and antennas, as well as the advantages of optical over conventional techniques. The ultimate figure of merit for the efficiency of optical control is the required total optical power needed to perform a specific microwave function. Previously demonstrated optically controlled microwave circuits are either of analog type, where e.g. the bias of a varactor diode is varied optically [1], or of digital type in which the microwave switch is optically turned on and off [2]. In most switches demonstrated to date, optical power is used to generate carriers in microwave *pin* diodes [3,4,5]. A disadvantage of this technique is that, in general, photodiodes are lossy at microwave frequencies, and therefore reduce the Q-factor of the circuit or antenna [5]. We have also observed this quality-factor reduction in a tunable second-resonant slot antenna [7]. The reduction in Q, however, enables a broad tuning bandwidth of 1.5 GHz around 10 GHz with at most 1 mW of optical power. This antenna is shown in Fig.1a, where a commercial photodiode (Fermionic FD300S3) is epoxied at the open end of a microstrip feed line, and a multimode fiber is epoxied to the active area of the photodetector. The measured tuning range, Fig.1b, shows that for optical powers between 0.06μW and 0.1mW, a continuous tuning of 1GHz is obtained. These results demonstrate the feasibility of relatively large analog tuning ranges (12% in the case of the antenna in Fig.1a) using optical control, with the expected associated tradeoff in antenna efficiency.

Another disadvantage of using optical power to generate carriers in microwave *pin* diodes 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 [6]. The optically controlled digital microwave SPDT 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 and remain constant.

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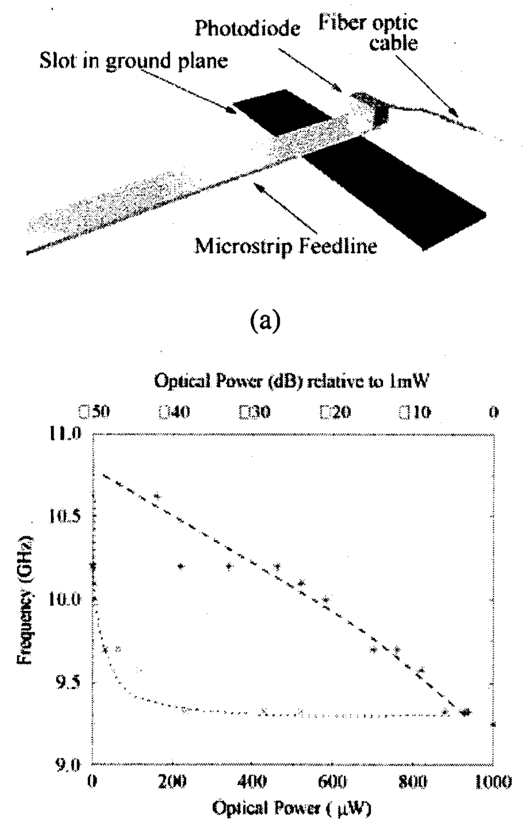


(a)

(b)

Fig.1. (a) Schematic of an optically-tuned slot antenna and (b) measured tuning range as a function of optical power (both linear and log scales in optical power are shown for clarity).

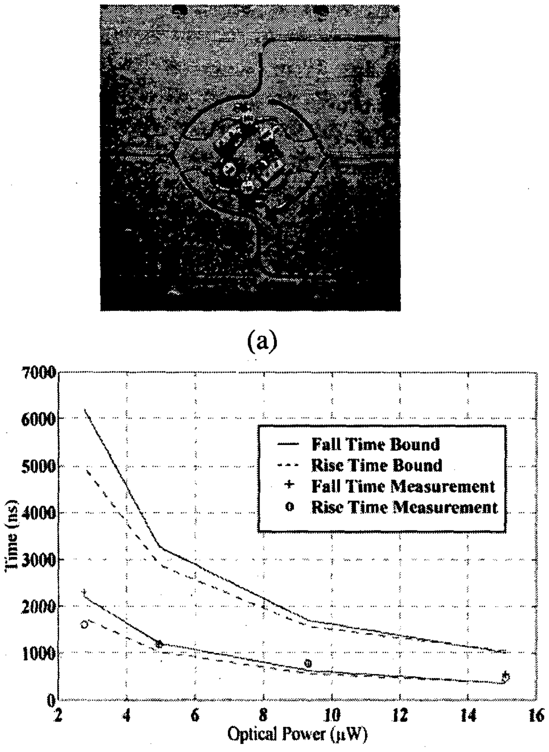
The SPDT switch is integrated with MMIC power amplifiers (PAs), low-noise amplifiers (LNAs) and patch antennas in a transmit/receive (T/R) active antenna in which the switching between T and R is accomplished optically in such a way that the switching speed is controlled by the amount of optical power. This active antenna is then used as the element of a half-duplex quasi-optical T/R lens antenna array. The switching speed of the array is independent of its size, and optical fibers that carry the switching control signals do not affect the microwave radiation.

Compared to standard phased arrays, such active lens arrays have been demonstrated to have improved dynamic range in reception, higher effective radiated power in transmission, graceful degradation, and allow for phase-shifterless beamforming [8]. The active array presented in this paper is designed to be the front end of an adaptive system, in which the signal processing can be accomplished with either a nonlinear analog holographic optical processor [9], or with standard DSP algorithms. The advantage of the optical processing is in the design simplicity, large processing bandwidth, and possibly lower overall DC power consumption.

II. LOW-POWER OPTICALLY CONTROLLED MICROWAVE SPDT SWITCH

The optically controlled SPDT X-band switch is shown in Fig.2a. 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. Compact high-pass (HPF) and low-pass filters (LPF) are needed to separate the bias/control and RF signals. A second order HPF isolates the bias control for each side of the SPDT switch, with 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 transmission loss at the bias line junction.

The optically-controlled bias to the *pin* diodes is implemented with a HP ATF26836 general purpose MESFET 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 MESFET gate capacitance and PD on-resistance dominate the rise and fall times of the bias control circuit. SPICE simulations indicate that the fastest expected rise (fall) time 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 time is approximately 2000ns.



(a)

(b)

Fig.2. (a) Photograph of back-to-back optically controlled SPDT X-band switch. (b) Measured and predicted rise time as a function of optical power.

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, Fig.2b. The bounds result from uncertainty in optical power delivered to the PDs, which in our setup varied by +1.7dB and –2.7dB.

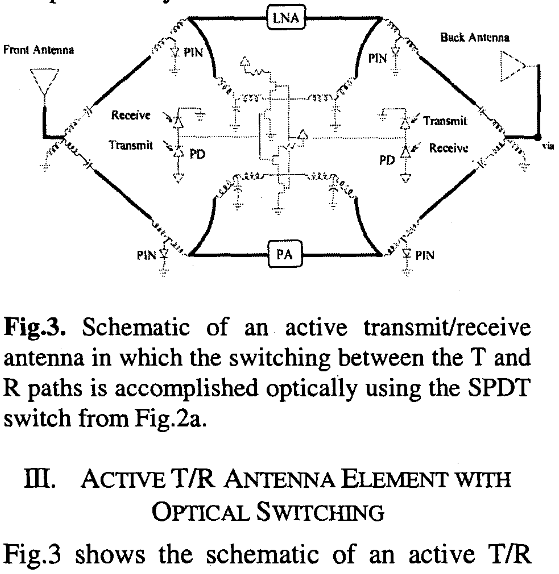


Fig.3. Schematic of an active transmit/receive antenna in which the switching between the T and R paths is accomplished optically using the SPDT switch from Fig.2a.

III. ACTIVE T/R ANTENNA ELEMENT WITH OPTICAL SWITCHING

Fig.3 shows the schematic of an active T/R antenna, which can be viewed as a bidirectional repeater [10]. 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) and LNA (United Monolithic Semiconductor CHA2063). An optical mount aligns the optical fibers to the PD with an accuracy of 200μm, limited by the packaging of the commercial PD. The measured SPDT switch in the active antenna element has an IL of 0.31dB and an isolation of 36dB over a 2.5GHz bandwidth.

Based on power and path loss measurements calibrated to an aperture the size of a unit cell ($0.75\lambda \times 1\lambda$), the gain contributed by the amplifiers is calculated 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.

IV. DISCUSSION

The active antenna presented in the previous section is used as the element of a quasi-optical lens array, similar to the ones described in [8]. The optical control of such an array has multiple advantages over electronic control: the control signals do not couple to the RF signals and the fibers do not affect the radiation; and individual control of each unit cell of the array increases the switching speed making it the same as that of a single element. The array is designed using off-the-shelf components not optimized for speed or low power. The rise and fall times of the microwave switch are determined by the optical power, allowing the switch to be tailored to the application. Even though the 2.6-ns speed demonstrated in this paper requires relatively large optical power (about 10mW), the optical energy is low, equal to 21pJ, since the high power is only required during the rise time. For comparison, the fastest reported MEMS RF switch has a rise time of about 1μs and requires about 2nJ of control energy [11].

ACKNOWLEDGEMENTS

This work was funded by ONR and the Office of the Secretary of Defense through the MURI program grant N00014-97-1-1006 and by Caltech through a ARO MURI in quasi-optical power combining grant DAAH04-98-1-0001.

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