Optically Controlled Photoconductive N-Bit Switched Microwave Signal Attenuator

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Abstract—**An optical architecture for N-bit digital control of microwave signals is introduced that uses the photoconductive effect in microwave waveguides for variable rf attenuation control. A 2-bit optically controlled microwave attenuator based on a transmission line fabricated on a silicon photoconductive substrate is experimentally demonstrated at 990 MHz. This attenuator provided 0, 5.8, 11.2, and 15.6 dB of independent optically switched attenuation levels.**

I. Introduction

MANY microwave signal processing systems require variable amplitude control of microwave signals. An excellent example, where perhaps thousands of independent amplitude controllers are required, is the phased array antenna. In this case, each antenna element is linked to a separate signal attenuation device that provides a grey scale attenuation function. These attenuator modules perform the necessary system signal calibration and antenna windowing functions. Today, for most deployed high-performance antenna systems, these phase and attenuation control devices are made from electronic switching devices such as p-i-n diodes embedded in microwave transmission line structures. A typical digitally controlled attenuator module contains a current-controlled p-i-n diode attenuator connected to an rf circuit, and a driver circuit consisting of a digital-to-analog (D-A) converter, and a voltage-to-current (V-C) converter. This attenuator module generally has a 4.6×4.6 cm area with a height of 2.2 cm, with an N-bit input port and a power supply port [1]. Thus, it is clear that electronically controlled microwave attenuator modules in a large (>1000) array application require significant electronic control hardware, such as thousands of N-bit digital feed lines, N-bit D-A converters, extended power supplies, and V-C converters.

In this letter, we propose using optically controlled variable microwave attenuators that could reduce a significant portion of the antenna panel electronic control hardware. In particular, we have recently shown how the photoconductive effect in a coplanar waveguide (CPW) transmission line, fabricated on a silicon substrate, can be used for over 30 dB of rf attenuation control using a 830-nm optical beam [2]. In this letter, we show how the photoconductive rf attenuation effect can be used to provide the grey scale N-bit digital format required for antenna array applications. This optically controlled attenuator scheme could provide many benefits to the antenna system designer, such as smaller electromagnetic interference (EMI) effects, lower rf propagation and insertion losses, remote control, and larger antenna panel open areas for radiator layout and other array functions.

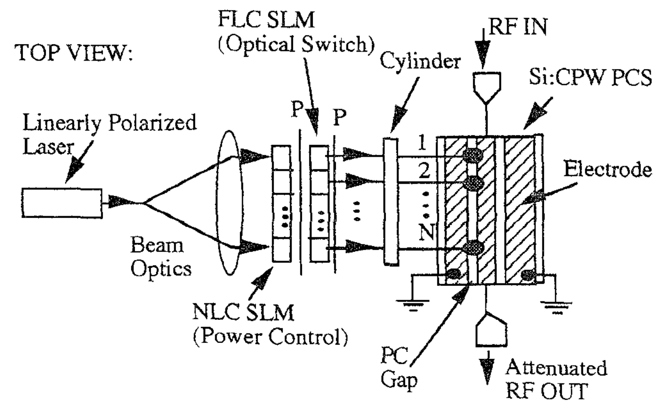

Fig. 1. A typical optically controlled N-bit attenuator using a Si:CPW-PCS that is controlled by N variable power switched light beams.

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II. Optical Control Technique for N-Bit Microwave Attenuation

Phased array antennas typically employ advanced solid-state circuits, the most typical being the monolithic microwave integrated circuit (MMIC). The common feature of MMIC's is their high-speed transmission structures that facilitate the transmission of microwave signals, either from the transmitter to the radiating element or from the radiating element to the receiver. In the envisioned case for future phased arrays, the actual radiating element would reside directly on a MMIC transmit-receive (T/R) module chip. Thus the transmitter, receiver, and radiator functions will all be monolithically integrated on a single semiconductor substrate. In either case, high-speed (i.e., microwave, rf, etc.) signals are routed within each chip by high-speed transmission lines. These T/R modules are all fabricated on semiconductor substrates, with the most typical being silicon (Si) and gallium-arsenide (GaAs) for low- and high-frequency MMIC's, respectively. Not only are these substrates necessary for the realization of advanced T/R modules, they are also photoconductive (PC) by their very nature. Photoconductors are materials that create electron-hole pairs from incident optical photons. Therefore fabrication of high-speed transmission lines on semiconductor substrates

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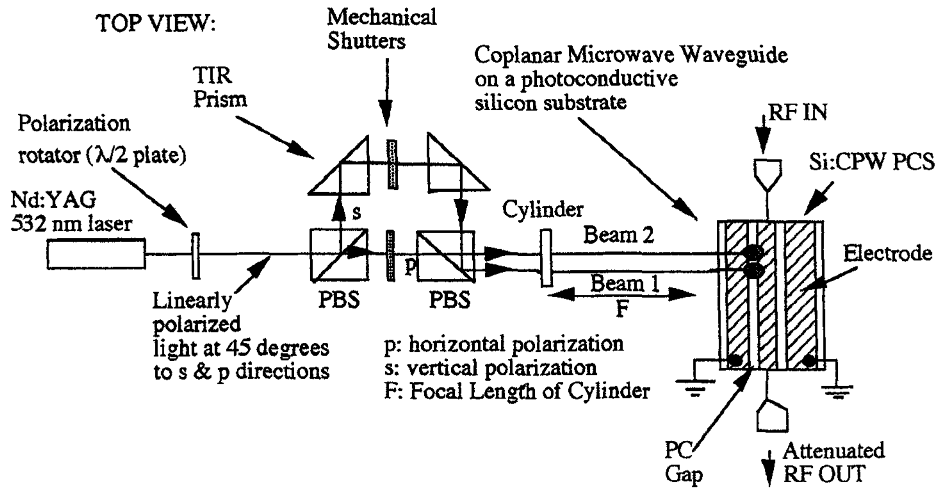

Fig. 2. Experimental setup to demonstrate the concept of an optically controlled variable switched microwave signal attenuator. The system is tested as a 2-bit or four-level optically controlled attenuator at 990 MHz.

yields high-speed PC switches (PCS's).The presence of light on the PC substrate leads to the generation of electron-hole pairs, which results in the creation of a solid-state plasma in the semiconductor. The interaction of the optically generated solid-state plasma with a propagating microwave signal on the high-speed T/R transmission line is the basis for operation of our attenuator. We intend to use this solid-state plasma/microwave interaction to attenuate the amplitude of the propagating signal. The preliminary basis for this work has been demonstrated earlier [2]–[4]. However, to date a practical N-bit attenuator for radar applications, and more particularly for phased array antenna control, has not been suggested using this PC technique.

Fig. 1 shows the proposed layout for N-bit microwave attenuation control implemented by free-space optics. Linearly polarized light from a laser is expanded and collimated. This light then passes through a sequence of components that include a one dimensional (1-D) N pixel nematic liquid crystal (NLC) spatial light modulator (SLM), a polarizer P, a 1-D N pixel ferroelectric liquid crystal (FLC) SLM, a polarizer P, and a cylindrical lens. The cylindrical lens focusses the N light beams onto one of the PC gaps between the coplanar waveguide metalizations on the silicon substrate that forms the Si:CPW-PCS. The NLC SLM, coupled with a polarizer, acts as a grey scale optical valve, where different pixels in the device are set to allow different power levels for the N individual optical beams. To form a binary N-bit attenuator, the N control beams must have different power levels that follow a binary pattern. For example, for a 3-bit design, the attenuator should give a total of eight attenuation levels. To achieve this, the three different control beams (called 1, 2, and 3) should cause individual attenuations of $K, 2K$, and $4K$ dB, respectively, where K is the smallest attenuation control possible with this binary N-bit design. There are several different ways to achieve this variable optical power distribution. These include grey-scale SLM switching, as in Fig. 1, variable ratio optical power splitters, and variable gain/power laser arrays [5]. Note that the N optical beams can also be remotely delivered by the individual optical fibers that terminate at various locations along the PCS. Once variable optical power distribution has been achieved, the next step is to rapidly switch these beams onto the PCS. As shown in Fig. 1, this can be done by a high-speed (e.g., 10 μs) on/off mode SLM, like the FLC SLM, that acts as a programmable half wave plate (HWP), which when fully "on" rotates the light polarization by 90 degrees. When laser arrays are used for the attenuator, no SLM's are required for power control and switching, as the lasers can be directly switched on and off with variable gains.

III. 2-Bit Optically Controlled Microwave Attenuator Experiment

To demonstrate the concept of a variable N-bit optically controlled microwave attenuator using the photoconductive effect, we set up the experiment shown in Fig. 2 that demonstrates a 2-bit attenuator using two control beams. The Si:CPW-PCS used had a 10-μm photoconductive gap between the coplanar waveguides. The overall test device length is 1.6 cm, with a measured rf insertion loss of 10 dB at 990 MHz. This Si:CPW-PCS has been described earlier [2], but in summary consists of a CPW geometry used to fabricate the switch contacts, which, having been placed on a suitable photoconductive substrate, serve to form the PCS. Previously, we had shown experimentally that for a given optical spot illuminating a certain section of the microwave transmission line, increasing the laser spot power eventually saturates the maximum attenuation level possible. Thus, further increase of the laser power does not result in greatly increased rf attenuation. This is because the attenuation value is approximately an exponential function of the induced plasma density, where the plasma density is linearly related to the spot optical power [2]–[4]. In fact, it was earlier demonstrated that tailoring the optical beam profile to an elliptical geometry increased the attenuation by 20 dB for a fixed laser power [2]. In this letter, we use a spatially distributed illumination of the PCS (e.g., using

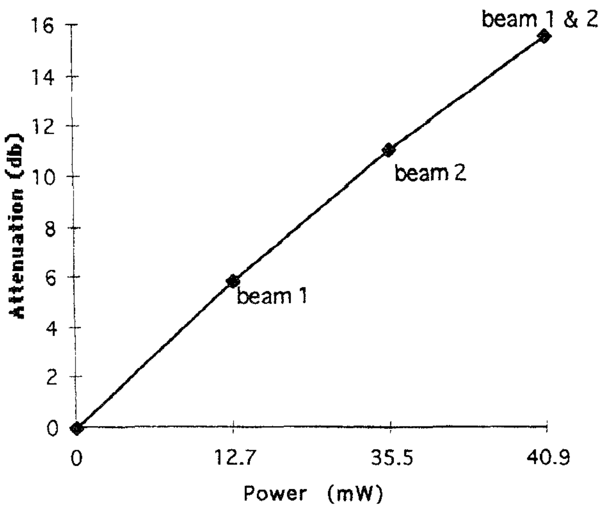

Fig. 3. Experimental results from the four-level (or 2-bit) optically controlled attenuator showing four different attenuation data points. Note that beams 1 and 2 are designed to give different attenuation levels to generate 2-bit control.

multiple spots) to avoid the attenuation saturation effect. In this way, the PCS can be designed to give an overall higher attenuation for a given laser power. Moreover, as mentioned, if the powers of the multiple spots are different and the beams can be independently switched on and off, it is possible to make a switched N-bit attenuator using N beams. For the experiment, linearly polarized light at 532 nm from a high power (>50 mW) frequency doubled Nd-YAG laser is incident on a $\lambda/2$ plate that is used to rotate the plane of polarization of the incident light that then strikes a cube PBS. Total internal reflection (TIR) prisms and another PBS are used to redirect the two beams towards a 10-cm focal length cylindrical lens that focusses the light onto one of the PCS gaps. The two spots illuminating the gap are each approximately 10 μm × 3 mm. By a slight shift in one of the prisms, the two spots were positioned side by side on the PCS gap. These beams could then be rapidly switched on and off via an optical switch such as an FLC SLM. To demonstrate the switching principle, we used mechanical shutters to block the light when required. A −10 dBm level 990 MHz signal was directly fed into the Si:CPW-PCS. The output from this device was connected to a spectrum analyzer that gives a rf power level of −24.4 dBm when no light is incident on the PCS. This 14.4-dB insertion loss is a combination of the PCS loss and the rf cable and connection losses.

The powers in the two beams are adjusted so that we get the following relationship for the four different attenuation settings: 0, $K, 2K$, and $3K$ dBm, where K is the resolution of the attenuator. In our case, beam 1 (12.7 mW) gives a −30.2-dB reading; beam 2 (28.2 mW) gives a −35.5-dB reading; both beams on (40.9 mW) give a −40.0-dBm reading. This means that the four attenuation levels for our attenuator are 0 dBm (no light), 5.8 dB (beam 1), 11.1 dB (beam 2), and 15.6 dB (beams 1 and 2). Thus, in this case, K is 5.8 dB. For a true binary setting with $3K = 15.6$ dB, K needs to be 5.2 dB instead of 5.8 dB. Because in our experiment the two beam spots on the PCS gap are not spatially identical and the PCS response is not completely uniform over the length of the microwave waveguide, careful adjustment of optical power and beam shape and position is required to get an ideal binary attenuator. Nevertheless, we have shown an attenuator with approximately 2-bit performance. Fig. 3 shows the experimental data for this experiment. Note that the graph shows a near-linear response, indicating that we are operating at the most efficient/steepest part of the photoconductivity versus optical power exponential relationship; this is also considered to be an optimum from the point of view of laser power design.

In conclusion, we have experimentally demonstrated the concept of an N-bit optically controlled microwave attenuator based on the photoconductive effect in embedded microwave transmission lines. Using a laser, a pair of SLM's, and some simple bulk optics, one can construct an N-bit optically controlled attenuator that can benefit various radar applications in terms of remoting, EMI, and reduction in antenna control hardware size and weight.

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