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BIAS FREE OPTICAL CONTROL OF MICROWAVE CIRCUITS AND ANTENNAS USING IMPROVED OPTICALLY VARIABLE CAPACITORS

Amit S. Nagra, Olivier Jerphagnon, Prashant Chavarkar, Michael VanBlaricum*, and Robert A. York

ECE Department, University of California, Santa Barbara, CA 93106

* *Toyon Research Corporation, Goleta, CA*

ABSTRACT

Monolithic optically variable capacitors (OVC's) consisting of photovoltaic arrays integrated with varactor diodes are used in bias free optical control of microwave circuits and antennas. The improved OVC's presented here required only 450 μW of optical power for a 2.2:1 change in capacitance, a threefold reduction in optical power compared to previous results. Using these improved OVC's, bias free optical control of phase shifters and slot antennas has been demonstrated with the lowest reported optical power.

I. INTRODUCTION

Applications such as reconfigurable and frequency agile antennas, active antenna arrays, beam steering grids, etc. will benefit greatly from bias free optical control. The active devices embedded in these radiating structures require bias and control signals that are ordinarily provided over metal wires. However these metal wires interfere with the radiation patterns of the antennas/arrays because the induced currents on the metallic wires generate spurious radiation. Thus it is desirable that the bias and control signals be carried in to the devices on optical fibers [1]. Optical fibers do not perturb the antenna fields significantly since they are made of low permittivity dielectric material. Indirect optical control is ideal for such applications and bias free optical control of varactor diodes [1, 2], FETs [3], [4] and PIN diodes [5] has already been demonstrated.

Indirect optical control relies on a dedicated photovoltaic (PV) detector to convert the optical control signal into an electrical bias signal. The electrical output from the PV detector controls the operating point of the microwave device and thereby the microwave characteristics of the device. Since the optical signal performs both bias and control functions, there is no need for external bias circuitry and bias leads. Another advantage of indirect optical control is that the optical and microwave components may be optimized independent of each other since the optical detection and microwave functions are separated. Thus it is possible to design circuits such that there is no RF penalty for using optical control and at the same time make the optical detection process very efficient so that low optical power is required. Previously described work on indirect optical control [1, 4, 5] relied on commercially available components. These hybrid circuits were large in size making them unsuitable for embedding in high frequency circuits and antennas. Also, large area photovoltaic arrays have slow transient response due to large junction capacitance. To address these issues, miniature photovoltaic arrays were integrated with varactor diodes to form Optically Variable Capacitors (OVC's) as proposed by Toyon Research Corporation in [1]. The size of the integrated OVC's is substantially smaller than the corresponding hybrid implementations. The miniature photovoltaic arrays have yet another advantage- ease of coupling light into the device. The array size can be matched to the core size of commercially available multi-mode fibers thus enabling a simple butt-coupling scheme to illuminate the photovoltaic array. Large area PV-arrays need beam expanders and additional optics for efficient illumination of the array active area, thereby making the light coupling more difficult and expensive.

The previously reported [2] monolithic OVC required 1.5 mW of optical power to achieve a 2:1 capacitance change. It was determined that inefficient coupling of optical power into the photovoltaic array was responsible for the high power requirement. To address this issue a circular

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photovoltaic array with 10 series connected photovoltaic detectors was designed and integrated with Schottky varactor diodes. This new layout for the photovoltaic array improved the optical coupling and reduced the optical power requirements of the OVC by a factor of three to 450 μW. Several microwave circuits that incorporate the OVC's, such as tunable notch filters, phase shifters and tunable slot antennas have been designed, fabricated and tested. The performance of these circuits demonstrates the potential of the monolithic OVC technology for the indirect control of microwave circuits. The circuits required no external bias and were controlled using low optical power (450 μW). To the best of our knowledge, this is the lowest reported optical power for the bias free control of microwave circuits and antennas.

II. IMPROVED MONOLITHIC OVC

The simplified block diagram of the improved monolithic OVC is shown in figure 1 and is the same as that discussed in [2]. The improved OVC consists of a photovoltaic array that controls the reverse bias across a varactor diode. A change in the incident optical power leads to a change in the photovoltaic array output voltage. This varies the depletion width of the varactor diode and thereby its junction capacitance. Hence this arrangement makes it possible to control the capacitance using optical signals. There are several advantages to this method: 1) the optical signal is used for bias as well as control of the active device thus eliminating the need for external bias. 2) Since the photovoltaic array drives a reverse biased varactor diode (low leakage current) the optical power requirements are small. 3) The optical detection and variable capacitance functions are provided by separate components and hence it is possible to optimize them independently. The varactor diodes are designed to provide the desired capacitance swing with the lowest possible RF insertion loss while the photovoltaic arrays are designed to provide the desired bias swing across the varactors using as low optical power as possible.

Figure 2 shows a picture of the improved monolithic OVC fabricated at UCSB. The epitaxial layer structure and the fabrication process are similar to those discussed in [2]. The main difference is in the layout of the PV-array, which has been made circular with 10 wedge shaped PV-cells connected in series. This circular PV-array shape ensures that maximum possible light from the fiber is incident on the active area of the PV-cells.

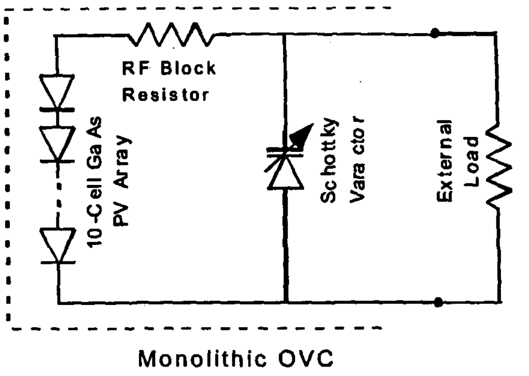

Figure 1: Circuit schematic for the OVC

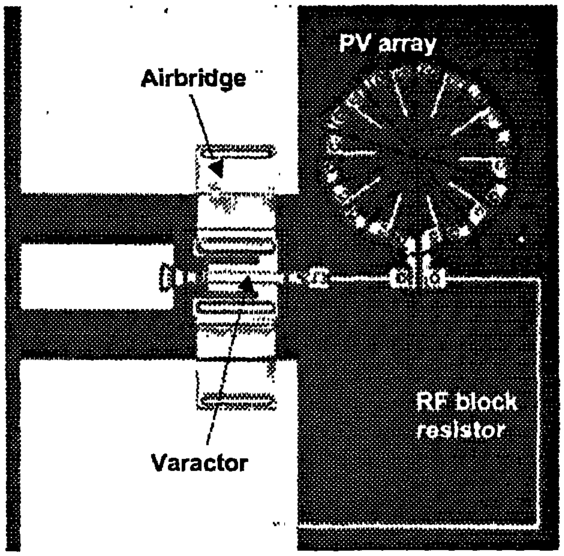

Figure 2: Picture of the improved OVC

III. MICROWAVE APPLICATIONS OF THE IMPROVED OVC

The improved monolithic OVC was placed at the end of a CPW transmission line structure to perform microwave measurements. Measurements were made on wafer using Cascade Microtech ACP40™ probes and a HP 8510 network analyzer.

Illumination for the OVC was provided by a semiconductor laser diode operating at 670 nm. The light from the semiconductor laser diode was launched into a multi-mode fiber with core diameter 200 µm, which was then butt-coupled to the OVC. The reflection coefficient (s_{11}) of the OVC was recorded for different illumination intensities. The measured s_{11} was fitted to an equivalent circuit model and a capacitance value was extracted. A maximum capacitance variation from 0.85 pF to 0.38 pF was possible using about 200 µW of optical power as shown in figure 3.

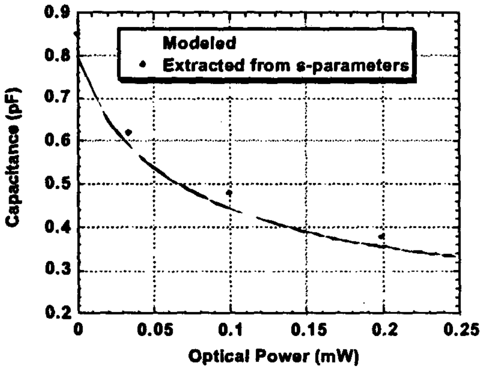

Figure 3: Capacitance versus illumination

Several microwave circuits incorporating the monolithic OVC as the optically controlled element were designed, fabricated and tested to demonstrate the potential of using the monolithic OVC. The circuits were fabricated on the same GaAs wafer as the OVC. One of the circuits fabricated was an optically controlled analog phase shifter operating in the X-band. A photograph of the phase shifter circuit is shown in figure 4. The circuit consists of a high impedance line periodically loaded with varactor diodes. In the small signal (linear) regime, the varactor diode loaded transmission line behaves like a synthetic transmission line whose phase velocity can be varied by changing the capacitance of the loading varactor diodes. Since all the varactor diodes require the same control signal only one PV-array is required for the circuit. The PV-array is connected in such a way that the array output voltage reverse biases all the varactors by the same amount.

The optically controlled phase shifter circuit generated a maximum phase shift of 175° at 12 GHz when the optical power was increased from 0 to 450 µW. Figure 5 depicts the phase shift and insertion loss for different optical power levels. The maximum insertion loss for this circuit was 2.5 dB and the return loss was better than 12 dB over all illumination states. The loss performance of this phase shifter (70°/dB) is significantly better than the optically controlled Schottky-contacted CPW phase shifters (~10°/dB) described in [6].

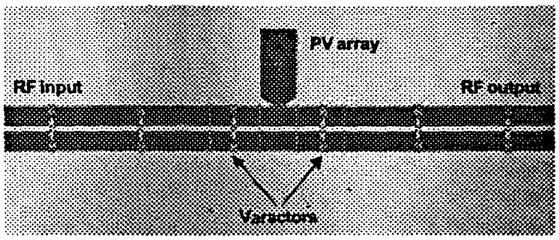

Figure 4: Optically controlled phase shifter

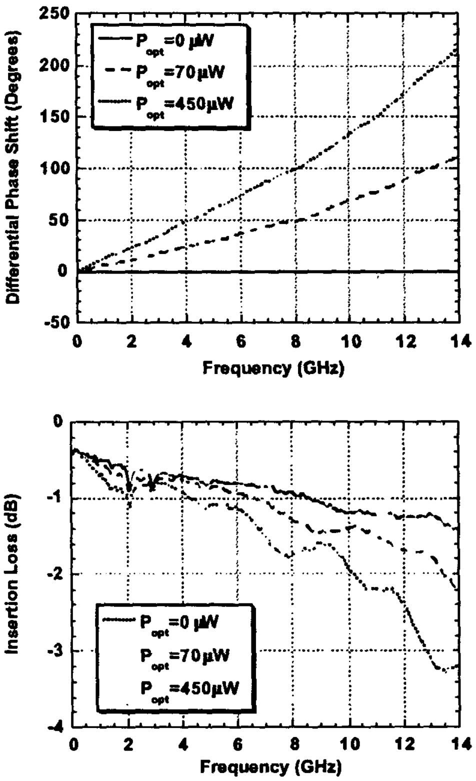

Figure 5: Differential phase shift and insertion loss versus illumination

An optically tunable folded slot antenna incorporating the OVC as the tunable element is shown in figure 6. The folded slot antenna was designed to be $\lambda/2$ long at 18 GHz. Due to capacitive loading of the antenna by the OVC, the resonance frequency was shifted down to 14.5 GHz. When optical power is incident on the OVC, the varactor capacitance decreases thus causing the resonance frequency to increase. Figure 7 shows that the folded slot antenna resonance frequency can be tuned from 14.5 GHz to 16 GHz by using just 450 µW of optical power.

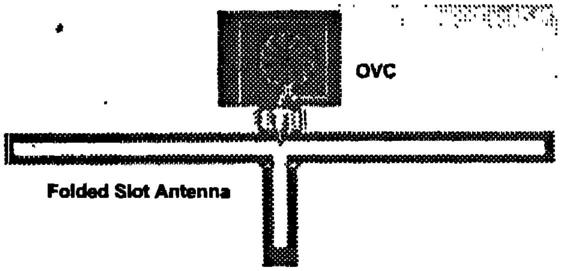

Figure 6: Optically controlled slot antenna

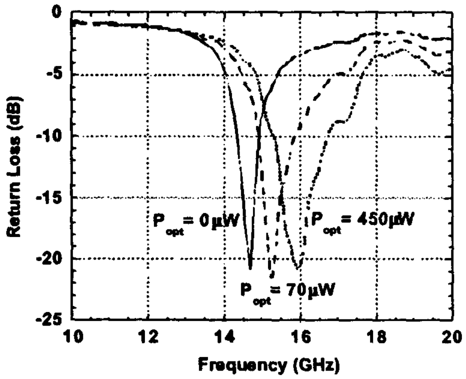

Figure 7: Return loss of folded slot antenna as a function of illumination

IV. CONCLUSIONS

The monolithic OVC has been improved to consume threefold lower optical power (450 µW) than reported previously. An optically tunable folded slot antenna with operating frequency tunable from 14.5 GHz to 16 GHz and an optically controlled phase shifter with 0-175° phase shift and insertion loss less than 2.5 dB were demonstrated using the improved OVC. Thus, bias free optical control of microwave components has been demonstrated using record low optical powers.

ACKNOWLEDGEMENTS

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