Low-Power Indirect Optical Reactance Control using Monolithic GaAs OVC™ Technology

Amit S. Nagra, Michael L. VanBlaricum*, Robert A. York

Electrical and Computer Engineering Department,
University of California at Santa Barbara, Santa Barbara CA 93106

**Toyon Research Corporation*
75 Aero Camino, Suite A, Goleta CA 93117}

Abstract

Electronic control of microwave antennas and circuits is usually based on the use of reverse biased semiconductor junctions. Optical control of such circuits has been by directly illuminating the active (depletion) regions of the semiconductor junctions. In this paper we report indirect optical control of microwave antennas and circuits using a photovoltaic array that generates a light dependent reverse bias voltage across a conventional varactor diode. This technique requires very little optical power, and allows for the independent optimizing of both varactor and photodetector performance. We report a monolithic implementation of the Optically Variable Capacitor (OVC™) circuit in GaAs using a novel lateral oxidation technique for device isolation.

Introduction

Tunable antennas have tremendous potential for use in shared aperture or frequency agile antenna arrays. One method that has been demonstrated [1] to be useful for implementing tunable antennas is the use of embedded reactive loads such as varactor diodes within the radiating structure. Thus by changing the value of the reactive loads the radiation characteristics, return loss, frequency of operation, etc. may be altered. Optical control of varactor diode reactance for reconfigurable antennas offers all of the advantages normally associated with optical links—low-loss, lightweight, immunity to noise, isolation from RF circuit—but has the additional advantage of extremely low optical power requirements as compared with other reconfigurable antenna technologies.

Varactor diodes may be controlled optically using two techniques: Direct Control, or Indirect Control. In direct control, the active region of the device is illuminated with the optical control signal. The same device thus performs both optical and microwave functions, which often involve contradictory design requirements. The maximum achievable capacitance tuning range is also limited for a given range of illumination intensities. Illumination of the varactor diode also leads to a reduction in the Q-factor of the diode. An alternative scheme is indirect control, where the optical control signal is first converted to a suitable electrical form by a dedicated detector. The electrical control signal governs the bias point of the varactor diode which is part of the microwave network.

In the approach used here, the optical control signal is converted to a light dependent voltage by a miniature photovoltaic (PV) array. The photovoltaic array comprises of Schottky or PN-junction diodes connected in series such that the open circuit voltages add up. The voltage developed across the PV-array reverse biases the varactor diode and hence controls the junction capacitance, as shown in figure 1a. Since the reverse biased varactor draws a small current, the voltage generated by the PV-array is essentially the open circuit voltage. Using this technique it is possible to obtain a larger swing in the voltage (and thereby in varactor capacitance) by simply using more diodes in series in the PV-array. The design is simplified because there are no microwave performance requirements on the PV-array and no optical functions to be performed by the varactor diode.

Two circuits for indirect optical control are shown schematically in figure 1. Figure 1a illustrates the basic concept, as described above. Figure 1b is a modification by Toyon personnel whereby the optically-induced bias voltage does not appear at the output terminals of the circuit, which would be connected to the RF circuit. This would be especially useful if multiple programmable reactances are required. This Optically Variable Capacitor (OVC™) circuit is made possible by the low drive currents required by the varactors (a negligible leakage current), which enables an RF choke resistor to be placed in the bias loop to present a high impedance to the RF circuit. In both cases a very large shunt resistor is required in parallel with the PV array to improve the induced voltage swing under low bias conditions.

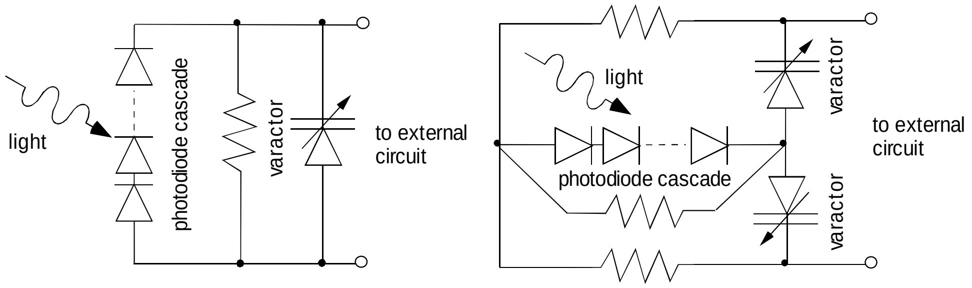

Figure 1 - (a) Basic concept of indirect optical control of varactors. (b) Toyon OVC™ circuit which isolates the optical bias from the RF circuit. In both cases a large shunt resistor is required in parallel with the photovoltaic cascade in order to realize maximum voltage swing

Photovoltaic Arrays

The first step in the fabrication of monolithic OVC's was the fabrication and testing of miniature photovoltaic arrays. The photovoltaic array had to be small so that the entire OVC could be embedded within a high frequency antenna. A prototype PV-array was implemented by connecting Schottky diodes in series by airbridges. The Schottky diodes were made on n-type GaAs with epilayers grown by MBE. The diodes were isolated by etching mesas down to the semi-insulating substrate around each device. The turn on voltage for the array is approximately 7 volts corresponding to about 0.7 volts per Schottky diode as expected. Early prototypes did not generate any open circuit voltage, and a close examination of the I-V curves for various levels of illumination showed photoconductor like behavior instead of photovoltaic behavior. This was identified to be a result of leakage through the substrate under illumination, and demonstrated the inadequacy of mesa isolation.

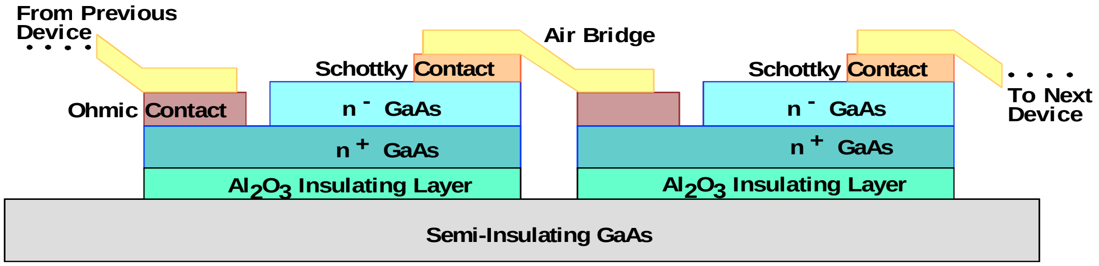

Figure 2 - Simplified cross section of the GaAs PV array and buried oxide layer for isolation.

In order to overcome this problem it was necessary to use an isolation scheme that did not degrade under illumination. This was achieved by lateral oxidation[2] of a AlGaAs layer (98% Al) that was included as the bottom most layer in the epistructure (figure 2). This truly insulating layer at the base of the mesas eliminated the leakage through the substrate. An SEM image of a PV array is shown in figure 3 below.

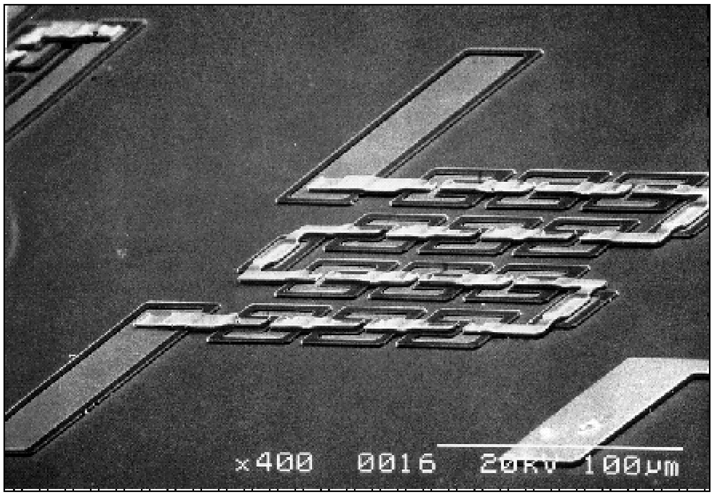

Figure 3 - SEM image of a 12-diode GaAs photovoltaic array fabricated at UCSB

The main quantity of interest for the OVC is the range of output voltages generated for a given range of illumination intensities. The maximum open circuit voltage available from a single diode is limited to the built-in voltage V_{bi}. Since Schottky diodes on GaAs have a lower V_{bi} than PN-junction diodes, we decided to implement the PV-array with PN junction diodes on GaAs. The epistructure was optimized based on the existing literature available for GaAs solar cells [3,4,5]. The active layer thickness was chosen to be about 3 absorption depths deep at 680 nm which was the wavelength of the incident illumination. The surface of the GaAs was passivated to reduce the surface recombination velocity by incorporating a AlGaAs layer (80 % Al) that was transparent to the incident illumination and at the same time did not degrade during the lateral oxidation of the buried isolation layer. The need for buried oxide isolation at the base of the diode mesas was verified by making a control sample without the oxide. The I-V curves under illumination for the sample with and without the oxide isolation scheme are shown in figure 4, and shows the efficacy of the oxide layer in reducing leakage through the substrate thus enabling larger output voltages. Further details regarding the processing conditions and device design can be found in [6].

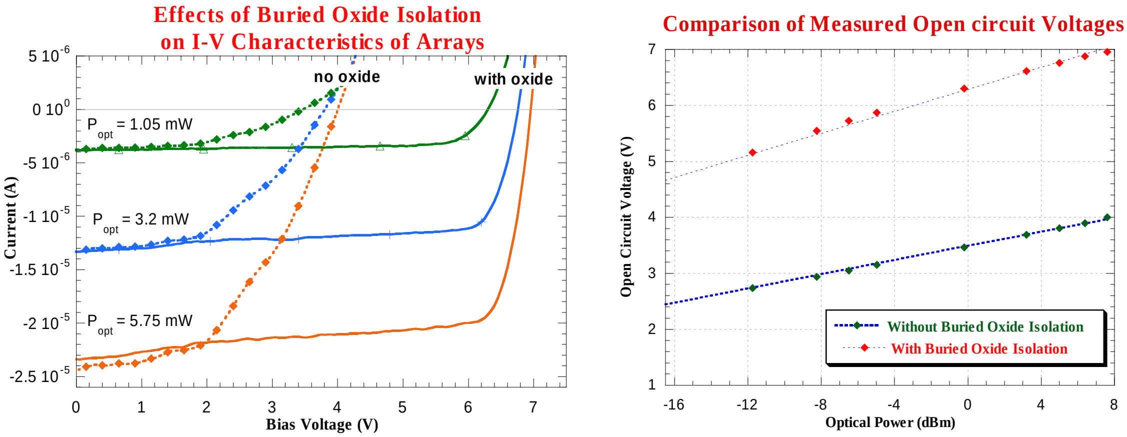

Figure 4 - Effects of the buried oxide isolation layer

RF Measurements

The PV-array implemented with PN junction diodes was integrated with a Schottky diode that was intended for use as a varactor. The varactor diode was placed at the end of a CPW transmission line structure to perform RF measurements, as shown in figure 5. The reflection coefficient S_{11} was recorded for different intensities of illumination over the range of DC-20GHz. The extracted RF capacitance at 10 GHz as a function of incident light intensity is shown in 5. We observed a maximum capacitance variation from 1.1 pf (dark) to 0.47 pf (optical power of 3.2 mW). This compares well with a theoretically predicted variation from 1.2 pf to 0.45 pf under the same conditions.

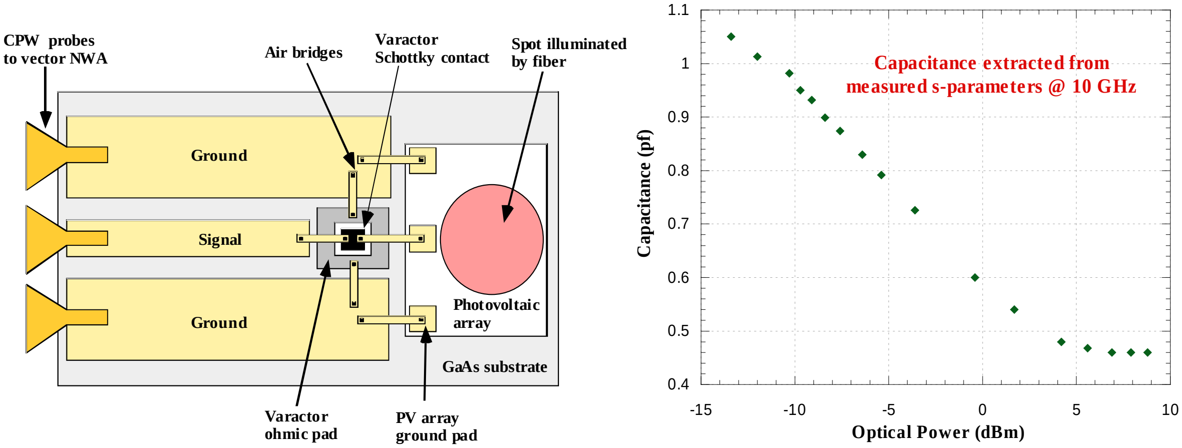

Figure 5 - OVC integrated in a cpw-line, and measured capacitance-vs-light curves

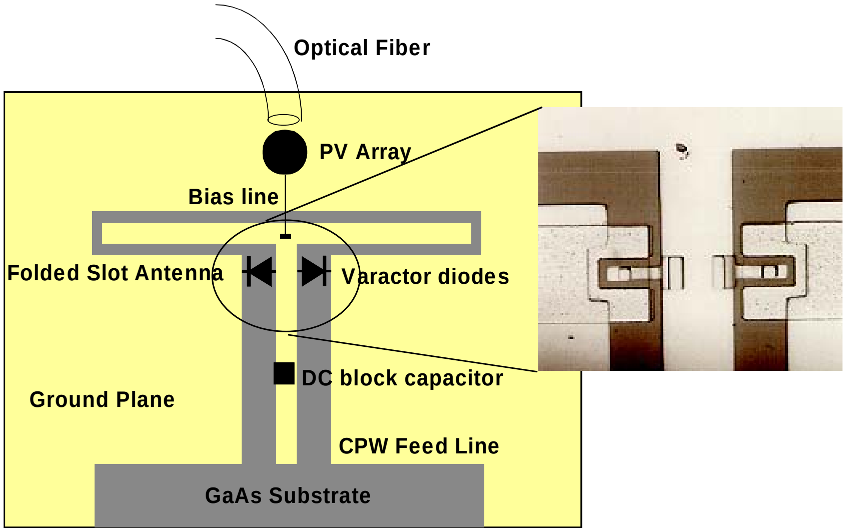

Figure 6 - Basic setup for a simple optically-tunable planar antenna, and SEM insert showing diodes integrated at the antenna feed.

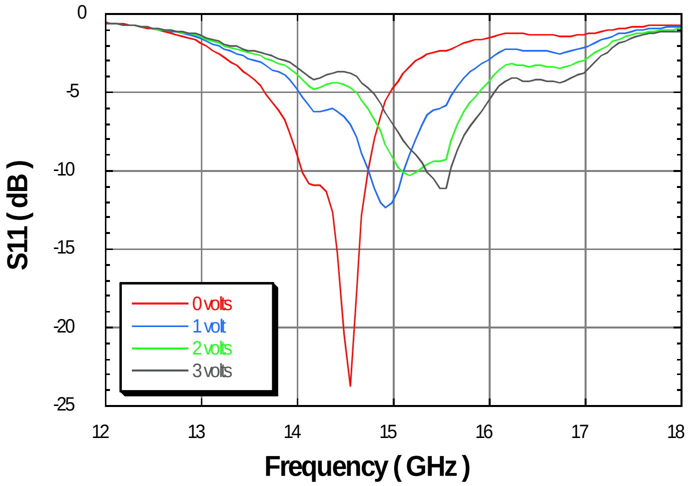

Figure 7 - Typical variation in folded-slot reflection coefficient versus diode bias.

The two types of OVC circuits shown in figure 1 can be easily integrated into a variety of microwave circuits and antenna structures. Some preliminary work on reconfigurable planar antenna circuits has been carried out using structures such as the one shown in figure 6 above. Measured variation in reflection coefficient (impedance) is shown in figure 7. Numerous other circuit topologies (phase shifters, filters, etc.) are currently being developed, and progress will be presented at the conference.

Summary

We have designed, fabricated and tested an Optically Variable Capacitor on GaAs. A buried oxide isolation scheme was incorporated to prevent substrate leakage that degraded performance of the miniature photvoltaic arrays. The performance of the PV-array and varactor were verified and capacitance versus light curves were generated. A maximum capacitance swing from 1.1 pf to 0.47 pf was recorded. This device has been integrated in planar antenna and other microwave circuit structures. Thus we have demonstrated a simple low-power technology for the optical control of microwave circuits and antenna arrays.

Acknowledgments

The authors wish to acknowledge the help of Prashant Charvarkar, who grew the MBE material used in this work. This work was supported by the Office of Naval Research.

References

[1] Michael L. VanBlaricum, Catherine J. Swann and Thomas L. Larry, "Remote Optical Control and Tuning of Antenna Elements," *URSI Digest*, Newport Beach, CA, USA June 18-23, 1995

[2] P.Parikh, P.Chavarkar, U.Mishra, "First Demonstration of GaAs on Insulator Technology," *54th Annual Device Research Conference Digest*, Santa Barbara, CA, USA June 24-26,1996

[3] J.M. Woodall, H.J. Hovel ,"High-efficiency GaxAl1-xAs-GaAs solar cells ," *Applied Physics Letters*, vol. 21, No. 8, October 1972

[4] J.C.C. Fan, A.R. Calawa, R.L. Chapman, G.W. Turner ,"Efficient shallow-homojunction GaAs solar cells by molecular beam epitaxy," *Applied Physics Letters*, vol. 35, No. 10, November 1979

[5] M.R. Melloch, E.S. Harmon, K.A. Emery ,"Large-area GaAs solar cells fabricated from MBE material," *IEEE Electron Device Letters*, vol. 12, No. 3, March 1991

[6] A.S. Nagra *et al.*, "Monolithic optically variable capacitors for tunable microwave antennas", *Proc. IEEE/Cornell Conference on Advanced High-Speed Device Semiconductor Devices and Circuit Concepts*, (Ithaca NY), August 1997.