A HIGH-SPEED PHASE SHIFTER BASED ON OPTICAL INJECTION*

L. R. Brothers, Jr. and C. H. Cox, III

Lincoln Laboratory, Massachusetts Institute of Technology
Lexington, Massachusetts 02173-0073

ABSTRACT

An optoelectronic analog phase shifter has been developed exhibiting 190 degrees of phase shift with no need for external bias. This is five times greater phase shift than previously reported for optoelectronic devices. The device characteristics are described and design considerations given. Performance data are presented demonstrating the high-speed modulation and wide-phase excursion capabilities.

INTRODUCTION

This paper discusses a high-speed analog phase shifter that has been developed using an optical varactor. The device presented here has a capacitance variation range an order of magnitude greater than has been previously reported (1), thereby enabling the realization of over 180 degrees of phase shift with no external bias supply, as was required with previously reported optically controlled varactors.

Test results are presented demonstrating equivalent performance of the optical varactor and a conventional voltage-controlled varactor diode in a reflection-type phase shifter. The optical-varactor phase shifter is expected to be an important addition to the rapidly expanding field of integrating microwave and optical technologies (2-5).

OPTICAL VARACTOR DISCUSSION

As an alternative to achieving phase shift with conventional varactors, this work investigated a variable capacitor controlled by optical signals. Basically, control of the capacitance is achieved by controlling the amount of charge that is optically injected into the depletion region of a photodiode.

There has been previous work along these lines, but which has met with only limited success. For example, Daryoush et al. (6) used an LED to illuminate a custom PIN photodiode. They reported capacitance changes of about 1 pF. As will be shown below, the present work used a laser source and a more conventional photodiode structure which together achieved capacitance changes of about 30 pF.

This increased range of capacitance change was made possible by two key factors. One was that the photodetector junction area was kept small, resulting in over an order of magnitude reduction in the unilluminated junction capacitance, as compared to the prior work. A smaller initial junction capacitance is important because fewer injected carriers are required in order to alter the capacitance significantly. In addition, fewer injected carriers means it will be possible to modulate the capacitance at a faster rate. The other key factor was the use of a semiconductor laser for the optical source. The laser is a more effective source than an LED for this application because it is easily capable of generating the relatively large number of carriers required in the small photodiode junction area.

In order to demonstrate the capacitance changes that can be achieved even with unoptimized devices, the experimental configuration shown in Fig. 1 was assembled. A high power GaAs semiconductor diode (7) laser with integral optical fiber was used to illuminate uniformly the active area of an InGaAs photodetector (8). The photodetector, mounted on a short microstrip, was connected directly to an RF impedance bridge.

The capacitance (measured at 100 MHz) plotted against optical power, with reverse bias across the photodetector as the parameter, is shown in Fig. 2. First, notice the significant capacitance change, which exceeds an order of magnitude. Second, notice that the optical power at which the capacitance begins to increase significantly is a function of the reverse bias, with greater powers being required as the reverse bias increases. As an important corollary to this second observation, note that a

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substantial capacitance change is achieved with zero volts, i.e., no reverse bias. Consequently, circuit applications of this device do not require bias supply elements. Third and finally, notice that for a given bias, there is a range of optical powers over which, to a good approximation, the capacitance is linearly related to the optical power.

PHASE SHIFTER DESIGN CONSIDERATIONS

In order to demonstrate the capabilities of the optical varactor in a straightforward yet realistic manner, a full 180 degree reflection phase shifter was designed. The required element values were calculated using standard design techniques. We chose a relatively low frequency (260 MHz) to perform the experiments in order to avoid obscuring the desired effect with parasitics. For comparison purposes, a phase shifter was designed using a conventional varactor diode, which was chosen to be similar in terms of capacitance and capacitance ratio to the optical varactor. Test configurations for both varactors are shown in Fig. 3.

Both parts of Fig. 4 plot phase shift versus the control parameter; in part (a) are the results of the conventional varactor with voltage control and in part (b) are the optical varactor with optical control and zero bias. In both cases, at least 180 degrees of phase shift was obtained. By applying 0.1 volt of forward bias to the optical varactor, a phase shift of 245 degrees was measured, as shown in Fig. 5. The associated insertion losses of both the conventional varactor and optical varactor phase shifters are plotted in Fig. 6.

A key area for investigation is extending the operation of the optical varactor to substantially higher frequencies, e.g., X-band. This in turn depends upon fabricating a photodiode with a smaller minimum capacitance and a wider bandwidth under high-level injection. While the varactor bandwidth is determined directly by the operation frequency of the phase shifter, the minimum capacitance is a function of the capacitance tuning range and the phase shifter frequency. For example, the results of a simple model relating the minimum capacitance values required for 180 degrees of phase shift versus phase shifter frequency are plotted in Fig. 7 for tuning ratios of of 2, 5 and 10. For a minimum capacitance of 0.1 pF, which is probably the minimum achievable value given the other device constraints, a photodetector diode with a tuning ratio of 10:1 will produce 180 degree phase shift at frequencies up to 14 GHz.

CONCLUSION

By scaling the device geometry, the optical varactor phase shifter can be designed for operation at microwave frequencies through X-band. This phase shifter has an increased tuning range over other devices reported and high modulation speed capabilities to meet future system requirements. The demonstrated performance proves the usefulness not only of this application but also the optical varactor's value for other conventional varactor diode applications, e.g., ultra-fast VCOs, frequency multipliers and attenuators.

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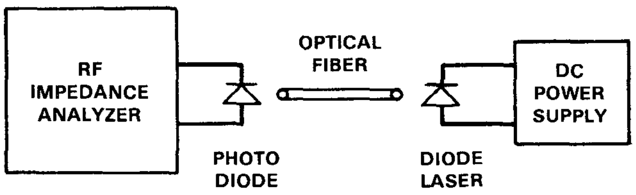

Fig. 1. Test setup for measuring capacitance of optical varactor.

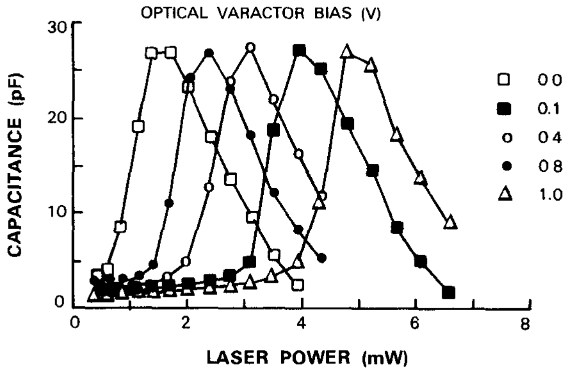

Fig. 2. Capacitance of optical varactor versus laser power with bias across varactor as the parameter.

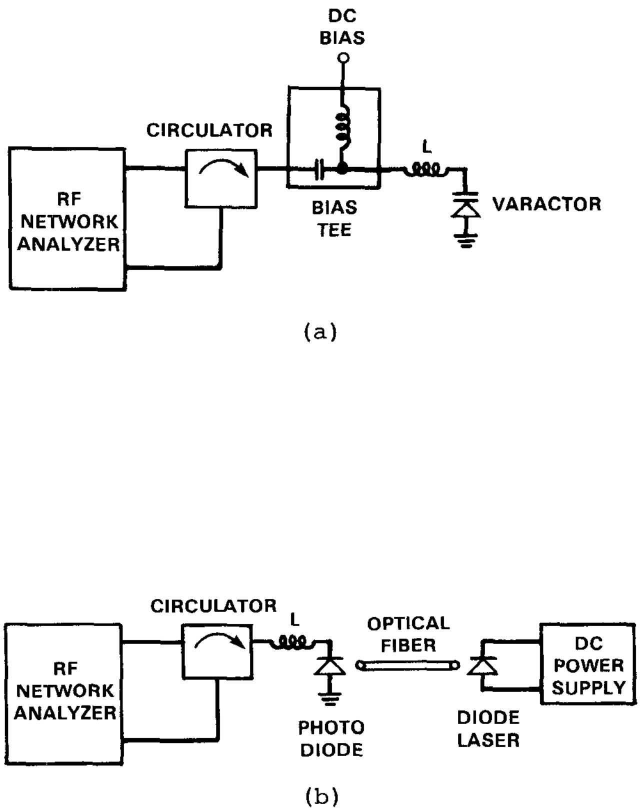

Fig. 3. Reflection phase shifter using (a) a conventional varactor, and (b) an optical varactor.

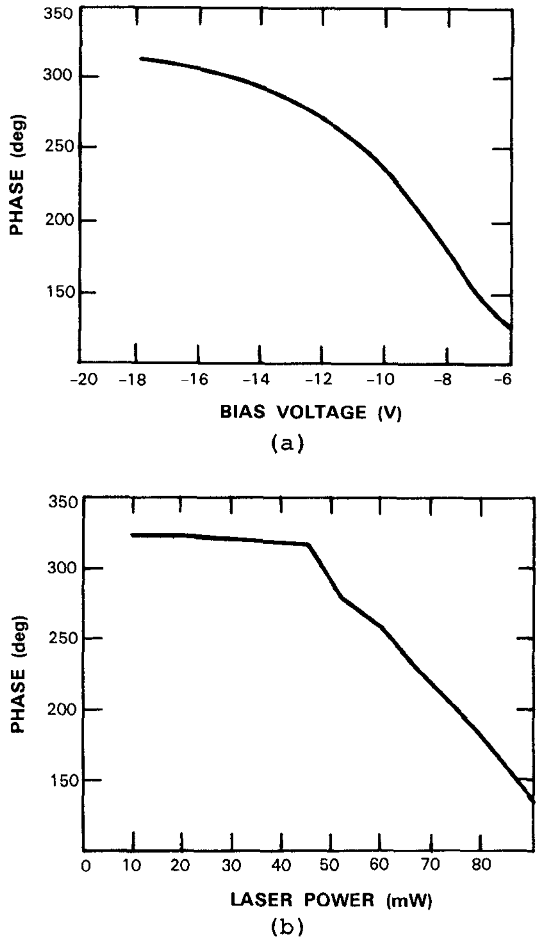

Fig. 4. Measured performance of (a) the conventional varactor phase shifter, and (b) the optical varactor phase shifter with 0-volt bias.

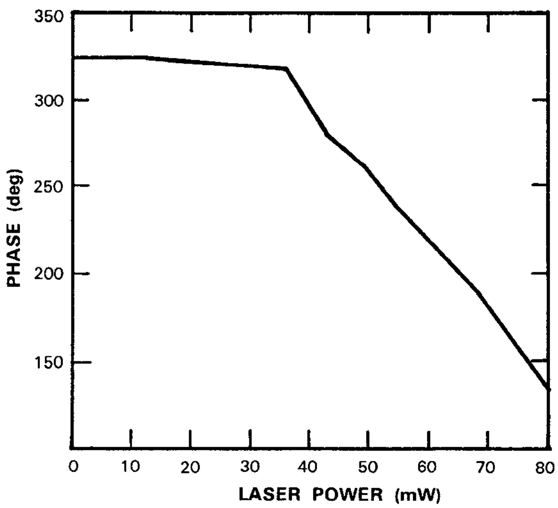

Fig. 5. Measured performance of the optical varactor phase shifter; 0.1-volt forward bias across varactor.

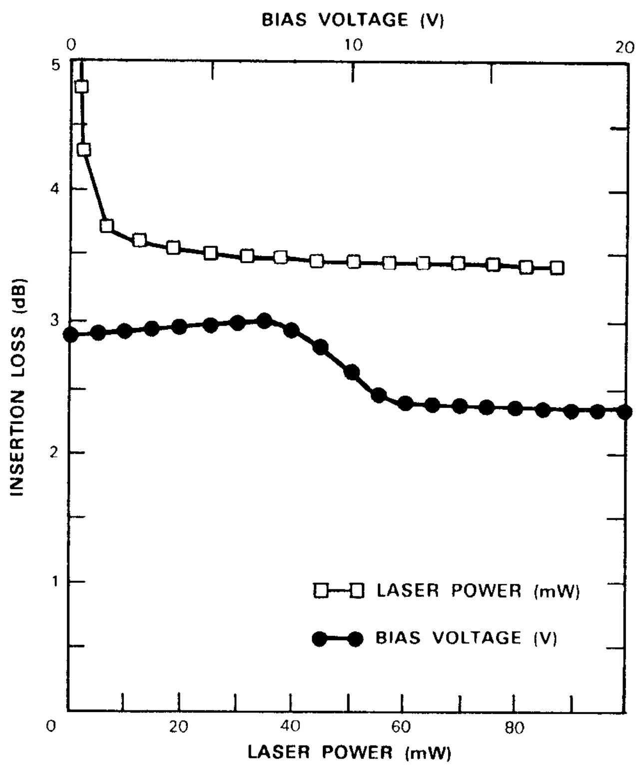

Fig. 6. Insertion loss of optical varactor and conventional varactor phase shifters.

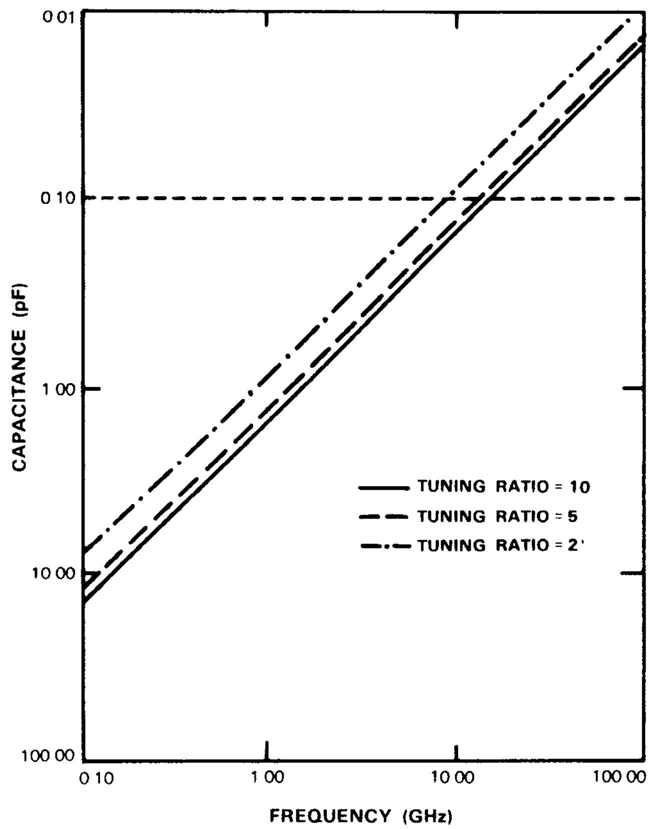

Fig. 7. Minimum capacitance for tuning ratios of 2, 5 and 10 (dotted line is at C = 0.1 pF).