ACTIVE PHASE SHIFTERS FOR THE MILLIMETER AND MICROWAVE BANDS

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ABSTRACT

Frequency agile, varactor controlled, Gunn active phase shifters for the microwave and millimeter wave bands are described. Demonstrated performance includes up to 160 degrees of continuous, electronically controlled active phase shifting at 47 GHz with 160 mw output and up to 320 degrees of phase shift at 94 GHz with 40 mw output.

INTRODUCTION

Expanding military system interests have created the need for new performance capabilities from solid state devices. This paper describes a frequency agile active phase shifter for the millimeter and microwave bands that provides in situ power generation and electronically controlled phase shift of the generated energy. Demonstrated performance includes up to 160 degrees of electronically controlled, continuous phase shift at 47 GHz with 160 mw output and up to 320 degrees of phase shift at 94 GHz with 40 mw output. Biphase modulation has also been demonstrated at 94 GHz with an active phase shifter. These results represent the highest frequencies at which an active phase shifter has been demonstrated.

DISCUSSION

The operation of the active phase shifter differs from that of FET active phase shifters that have been reported at microwave frequencies (ref. 1). The operating mechanism is based on the change in phase that occurs when the resonant frequency of an oscillator circuit is changed, but the frequency of oscillation is constrained from changing by injection (frequency) locking the oscillator to a stable frequency source. The frequency agile active phase shifter to be described is basically a widely tunable Gunn VCO that is operated in the aforementioned manner. When the VCO is varactor tuned to a desired frequency and then injection locked, a subsequent change in varactor voltage will result in a phase change of the output wave relative to the locking signal. When the VCO is unlocked, retuned to another frequency and relocked, phase control by varactor voltage adjustment is reestablished. Varactor controlled, continuous phase shift at constant frequency is obtained within the total locking range of the VCO.

The basic theory of injection locking has been described by Adler (ref. 2) and Kurokawa (ref. 3).

The analysis was extended to the large signal case by Paciorek (ref. 4). The resulting phase angle after locking of two signals initially separated in frequency was referred to as a phase error. In the active VCO phase shifter, functional use is made of this phase "error" to provide electronically controlled phase shifting. After the VCO is locked at a desired frequency, the phase of the generated energy will follow changes in varactor control voltage. This means of active phase shifting has been demonstrated up to 94 GHz but its use can be extended further into the millimeter frequency range.

An active phase shifter offers performance and size advantages in a phased array application. Since the device is active, it provides a spatial power combining capability, thereby eliminating the need for a central high power source and corporate feed as used in a conventional array. This is an important consideration at millimeter wavelengths. The potential for size reduction follows both from the dual function nature of the device and by the miniaturization provided by the lumped element circuit embodiment used for its fabrication.

An electronically scanned antenna array has been described in a patent by Glance (ref. 5) in which injection locked Impatt diode oscillators were used as active phase shifter elements. Phase shifting by control of the bias current of the Impatt diode was described. Rubin (ref. 6) has reported frequency agile phase shifting of injection locked YIG tuned oscillators. Controlled phase shift was reported in X band by DC voltage control in a phase comparitor feed back loop. A phased array based on this means of active phase shifting was described in a patent by Rubin (ref. 7). New results that are reported in this paper include the following:

- Use of varactor control in an active (Gunn) phase shifter (ref. 8).
- Demonstrated performance advantages that include broadband frequency agility, continuous and near linear

phase shift versus control voltage, high locking gain, flat output power and high modulation frequency (to 250 MHz).

- Active phase shifter performance at 47 and 94 GHz, the highest frequencies reported for this type of device.
- Demonstration of a 94 GHz active bi-phase modulator.
- Active phase shift enhancement (times N) by use of an Nth order frequency multiplier, a simplification to the use of cascaded active phase shifter stages (ref. 5).
- Demonstrated performance of an ultra-miniature Gunn VCO with a 6 GHz tuning range for use as an active phase shifter element.

DEVICE PERFORMANCE

A block diagram of a single stage active phase shifter is shown in Figure 1A. The maximum theoretical phase change with a single stage is ± 90 degrees. Phase shift greater than ± 90 degrees can be obtained by following the stage with a frequency multiplier of order N, as shown in Figure 1B. Phase shift is multiplied by the factor N which provides a circuit simplification to an alternate method of using N cascaded active phase shifter stages.

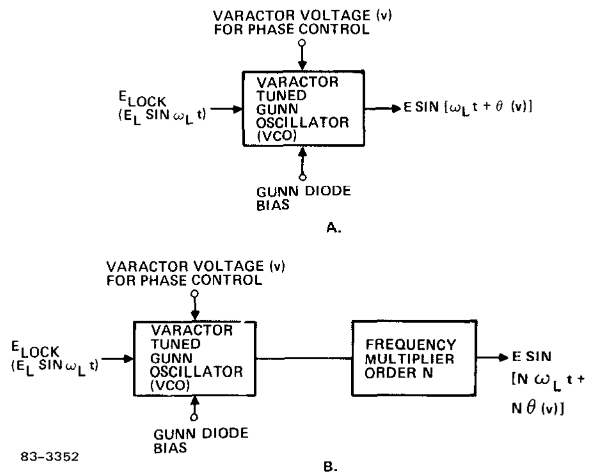

Figure 1. Block Diagram of Active Phase Shifter Configurations

The measured performance of a microwave active phase shifter, in the configuration of Figure 1A, is shown in Figure 2. Phase shift is plotted as a function of phase control voltage with locking gain as a parameter. A 9 to 14 GHz Gunn VCO in lumped element form was the active source. The VCO was set to a frequency of 12.85 GHz on its varactor controlled tuning range and then injection locked. Subsequent changes in varactor control voltage from the quiescent value produced the phase change of the VCO output (relative to the fixed locking signal) that is plotted in Figure 2. Total phase shift is seen to increase with locking gain. With a locking gain of 22.6 dB, total phase shift of 158 degrees was obtained with a control voltage range of 0.15V. At 13.6 dB locking gain, total phase shift was 121 degrees with a control voltage range of 0.38 volts.

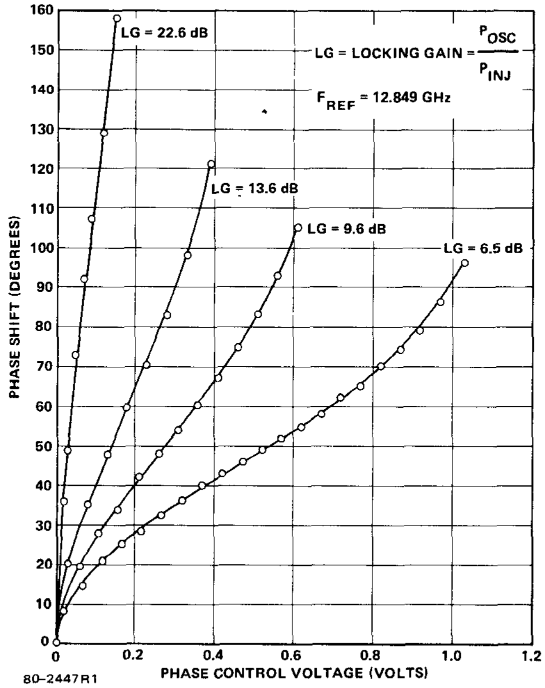

Figure 2. Measured Phase Change of Active Phase Shifter Versus Control Voltage

The measured performance of a frequency agile millimeter wave active phase shifter (Figure 1A) is shown in Figure 3. Phase shift as a function of control voltage is plotted with frequency as a parameter and constant locking gain of 22 dB. A commercial Gunn VCO with a center frequency of 47 GHz, ± 250 MHz tuning range and 160 mw output power was the source. When the VCO was injection locked to function as an active phase shifter at 46.75 GHz, a total phase shift of 162 degrees (± 81 degrees) was obtained with a control voltage range of 2.2 volts. Output power variation was ± 0.2 dB over the full phase control range. When locked at 47.25 GHz, the total phase shift was 139 degrees which was obtained with a control voltage range of 12 volts. The increase in control voltage range with frequency is reflective of the shape of the tuning characteristics of the VCO with its abrupt junction varactor. Uniform phase control voltage range with frequency can be expected with a VCO using a hyperabrupt junction varactor as the control element.

The 47 GHz active phase shifter was used in conjunction with a frequency doubler (Figure 1B) to produce 40 mw output at 94 GHz. The magnitude of phase change doubled from that measured at 47 GHz (Figure 3). The active phase shifter/doubler combination was used in a system application as a

+90 degree bi-phase modulator at 94 GHz with modulation frequency as high as 250 MHz. The results obtained at 47 GHz and 94 GHz represent the highest frequencies at which active phase shifter performance has been demonstrated.

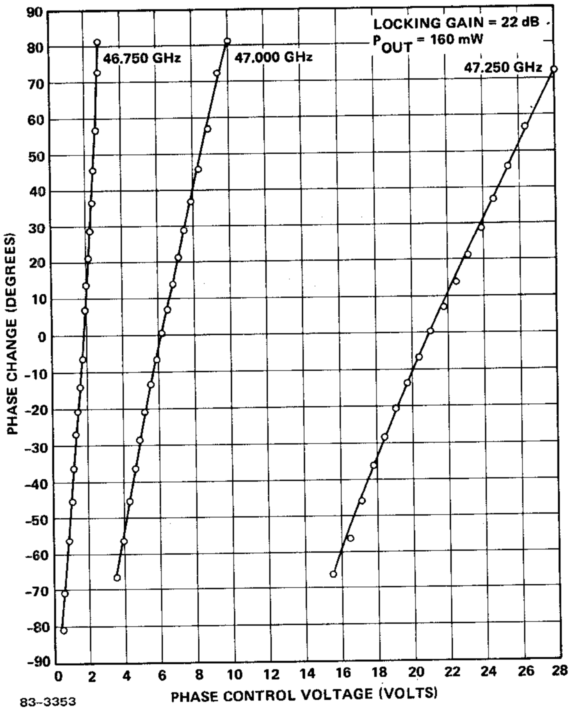

Figure 3. Active Phase Shifter - Measured Phase Change Versus Control Voltage

An ultra-miniature K_A band Gunn VCO was developed to further enhance the small size advantage offered by the dual function nature of an active phase shifter. The VCO was built in lumped element circuit form and its miniature size is illustrated in Figure 4A where it is compared to a match head. The VCO circuit (Figure 4B) is completely contained on the 0.115 inch flange diameter of the threaded stud of a commercial Gunn diode, as shown in a top view in the photograph. It tuned continuously from 26 to 32.4 GHz with a maximum output power of +10.6 dBm. A factor contributing to the wide tuning range (6.4 GHz) was the use of a lumped element circuit which is inherently more broadband than a distributed circuit. Linear tuning in the low frequency portion of the range resulted from the use of a hyperabrupt junction GaAs varactor. The drop-in nature and small size of the VCO circuit and its wide tuning capability are advantageous features in a phase array application. The size of the VCO is the smallest known to have been reported.

ACKNOWLEDGEMENTS

This work was performed at Eaton Corporation AIL Division, Melville, N.Y. The contributions of S. Nussbaum for evaluating the performance of the 47 GHz active phase shifter and E. Dolphy for VCO assembly are gratefully acknowledged.

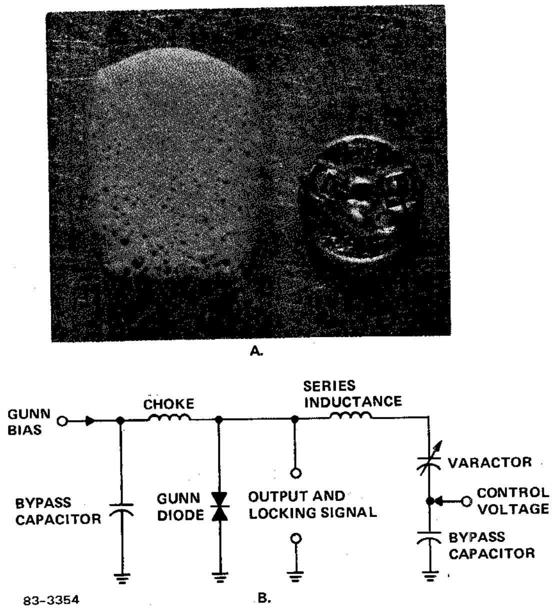

Figure 4. Miniaturized, K_A Band, Lumped Element, Gunn VCO

SUMMARY

The performance of frequency agile, varactor controlled, Gunn active phase shifters for the microwave and millimeter wave bands has been reported. The dual function nature of an active phase shifter and its small size provides a potential for the advancement of the state of the art in phased arrays.

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