OPTICAL CONTROL OF A DIGITAL PHASE SHIFTER

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ABSTRACT

A method for the optical control of digital phase shifters which significantly reduces the number of control lines required is described. The technique uses a simple cost effective LED source along with a MESFET detector and an A/D converter to generate the digital phase shifter command. The approach is independent of the phase shifter operating frequency and is compatible with MMIC technology and parallel optical signal processing. Experimental results are presented for the optical control of a 6-bit digital phase shifter. To provide 360° of phase shift, 310μW of optical power are required

INTRODUCTION

Optical signal distribution for phased array beamforming, including the optical control of phase shifters, offers several significant advantages such as reduction in size, weight, and improved protection against EMI[1]. Most monolithic digital phase shifters require a command in the form of an n-bit parallel binary word (where n is the number of phase shifter bits) to control the phase shift [2]. This requirement mandates a minimum of n separate control lines for each phase shifter. Moreover, certain types of digital phase shifters call for complementary control lines for each bit, thereby doubling the number of control lines required. Therefore, given that the new generation of large phased array antenna systems will utilize a large number (10^3-10^4) of MMIC T/R modules, it is desirable to devise methods for the optical control of digital phase shifters which can significantly reduce the number of control lines that must be routed to each T/R module.

One method to reduce the number of control lines that must be sent to each T/R module simply involves the transmission of serial phase shifter data along with subsequent demultiplexing and serial to parallel data conversion to provide the appropriate command to a number of phase shifters. A hybrid GaAs optical controller has recently been described which employs a high speed digital fiber optic link, a PIN photodetector, and MESFET demultiplexer that can distribute serial data to as many as 16 phase shifters[3]. We propose a technique to feed the control information to the T/R modules or subarrays via an optical intensity on a fiber which is compatible with optical signal processing procedures. The approach, depicted in Fig.1, utilizes a spatial filter to generate the appropriate control signals (optical intensities), a MESFET for the demodulation of the optical signal at the T/R module, and an interface (conditioning circuit) between the detector and the element (phase shifter, switch) being controlled. This technique is totally compatible with standard MMIC fabrication technology, requiring no additional processing steps.

Optical control of a 6-bit X-band phase shifter where an A/D converter is used to generate the required parallel digital phase shifter command is demonstrated. Only one fiber optic input for each phase shifter is required in addition to an A/D encode command. This approach is applicable to all known digital phase shifters, regardless of their operating frequency.

DESCRIPTION

All digital phase shifters consisting of n-bits may be optically controlled as described below. An intensity modulated LED or laser diode is coupled to an optical fiber which illuminates the active area of a MESFET serving as an optical detector. The intensity is varied to produce 2^n equally spaced discrete MESFET output voltages, which are appropriately scaled via a standard amplifier to correspond to an A/D converter input voltage range. The A/D converter then converts the

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voltages to an n-bit binary word which is used to command the phase shifter to a desired phase state. In this way, the intensity level of the incident optical input sets the phase shifter to the desired state.

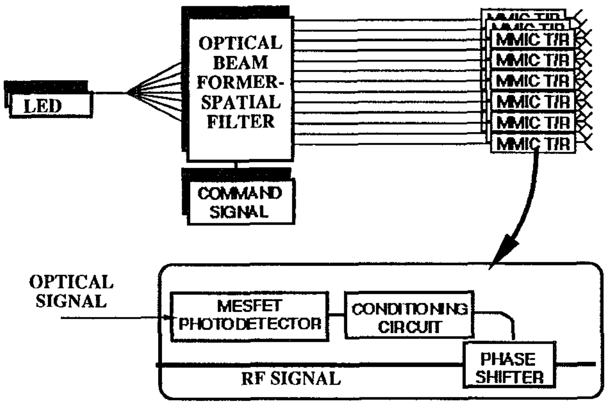

Fig. 1. Schematic diagram of the optical control of phased array antenna. Detail shows the optical microwave interface at the MMIC T/R modules.

Additional circuitry may be required to interface the output of the A/D converter to the phase shifter input and the A/D converter also requires an encode command to instruct it to digitize and thereby change the phase shifter state (if the optical intensity has changed). The A/D encode command will occur each time a change in the beam position in a phased array application is desired. This technique is fully compatible with available MMIC components, although MMIC A/D converters are not fully developed. It should also be noted that emerging parallel optical signal processing may be used to simultaneously generate the appropriate intensity modulation for a number of phase shifters via spatial filtering. This aspect of the approach takes on added significance as the number of antenna elements and beam agility increases.

EXPERIMENTAL SETUP AND RESULTS

The experimental setup is depicted schematically in Fig. 2. The light source is a fiber coupled LED operating at 830nm. The core and cladding diameters of the multimode fibers are 100µm and 140µm respectively. The MESFET has a 1mm gate length and 300µm gate. It has four 75µm gate fingers and it is operated in the common source configuration near pinchoff (Vgs=-2.4V) for optimum light responsivity. The fiber is positioned over the active area of the FET using a micropositioner to achieve maximum optical coupling. An inverting operational amplifier with a gain of 40 is used to scale the FET detector output voltage to the 10V A/D converter input range. The six most significant bits of a conveniently available 12-bit parallel A/D converter were used to effectively provide a 6-bit converter with an associated quantization level of 156mV.

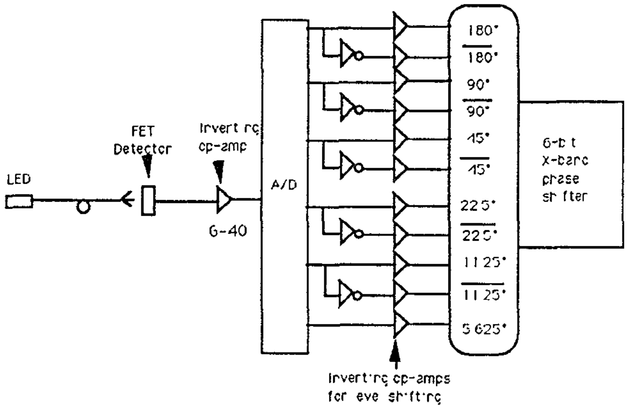

Figure 2. Experimental setup.

The digitally-controlled MMIC phase shifter used in this experiment is a Wideband 7-11GHz Six-Bit Phase Shifter developed by GE under an IR&D program in 1987. The six control bits are designed to minimize sensitivities of the circuits to process variations while maintaining low RMS phase error over a broad bandwidth. The schematic diagram of each bit is shown in Fig. 3 and the photograph of the phase shifter is shown in Fig. 4. The 5.6° bit is a simple resonated FET where the spiral coil Q is adjusted to achieve equal insertion loss for both states of the bit. The 11.25° and 22.5° bits use a switched filter technique, where the two SP1 inductors and FET2 form a low-pass filter in one bit state, and the SP2 inductor forms a high-pass filter in the other bit state. This design technique results in low insertion loss, broad bandwidth and excellent phse shift. The 45°, 90, and 180° phase bits use a switched high-pass/low-pass filter technique, where the FET1-FET2 combinations form single-pole, double-throw (SPDT) switches at the input and output of each bit. The SP1 inductor and MIM1 capacitors form the low-pass filter, and the MIM2 capacitors with the SP2 inductor form the high-pass filter. The high-pass/low-pass bit technique is well suited for large phase shifts because the lumped elements are easily realized in MMIC form. The phase shifter performance across the 7-11GHz band has been measured over all possible 64 states. Insertion loss is 9.5 ± 1.5dB across all states and across the band. The optimized RMS phase error is less than 2.5° and the input and output return losses are better than 11dB.

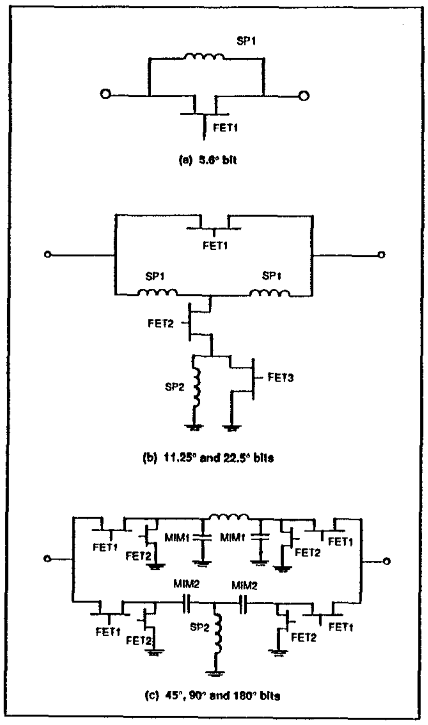

Fig. 3 Schematic diagram of the various phase bits for the 7-11GHz phase shifter.

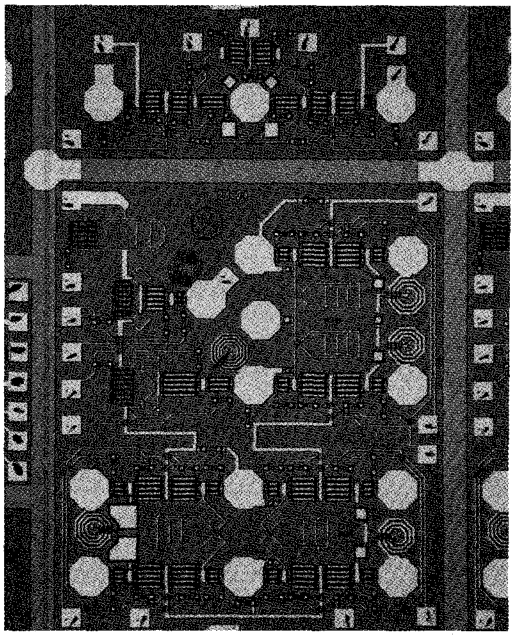

Fig. 4 Photograph of the phase shifter

Since the phase shifter bits require 0/-6V control voltages, level shifting circuitry is required to interface the A/D output to the digital phase shifter. This circuitry consists of logic inverters to provide the complementary voltages along with inverting amplifiers to provide the 0/-6V range. The experimental results, shown in Fig.5, display the phase shifter state as a function of the LED bias current. The nonlinear response is due to the LED-FET transfer function. The maximum optical power needed to control the phase shifter through all sixty-four states was 310μW. The MESFET was biased close to pinch-off in the dark state which assured both optimum sensitivity and noise characteristics.

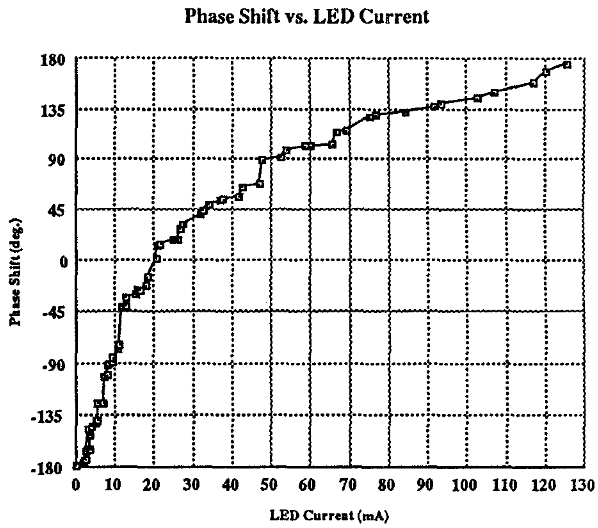

Figure 5. Phase shift v.s. LED bias current.

SYSTEM CONSIDERATIONS

The viability of our technique depends on the A/D input noise level as well as the precision to which the A/D input voltage can be optically controlled. The A/D input noise contains contributions from the fiber optic link consisting of the LED (or laser) and MESFET photodetector, as well as the associated level shifting circuitry. The A/D input voltage settability is determined primarily by the LED and FET detector characteristics. Since the performance of this technique is determined by the ability to generate a desired A/D output (phase shifter command) it is therefore important to describe the A/D output quantitatively in terms of the A/D input noise and quantization level.

The A/D converter transfer function has a staircase

The A/D converter transfer function has a staircase characteristic where the output contains an integer number of quanta, k, and the quantization voltage level, q, is determined by:

$$q = \frac{V_{FS}}{2^{n}}$$

where V_{FS} is the full scale A/D input voltage range and n is the number of bits.

The probability that a correct phase shifter command (A/D output) is obtained is given by:

$$P\left(\begin{matrix}\text{correct}\\ \text{command}\end{matrix}\right) = \frac{1}{2}\left\{ \mathrm{erf}\left(\frac{\frac{q}{2} - v'}{\sqrt{2}\,\sigma_N}\right) + \mathrm{erf}\left(\frac{\frac{q}{2} + v'}{\sqrt{2}\,\sigma_N}\right)\right\}$$

where σ_N is the rms noise voltage and v' is the input voltage.

The above expression, derived under the assumptions that the input voltage v' may be controlled to be within the desired quantization range ($-q/2 < v' < q/2$ for k=0) and that the A/D input noise is Gaussian, is valid for any A/D output since the statistics are identical for each output level. This expression, which is symmetric about zero volts, is plotted for input voltages ranging between 0 and .4q for different values of q/σ_N. This is shown in Figure 6:

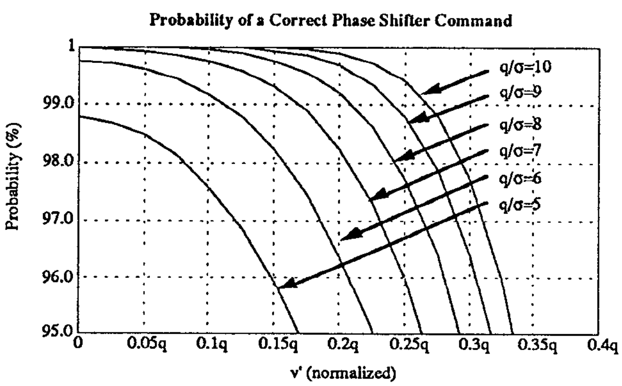

Fig. 6. Probability of generating a correct command

As evident from Fig. 6, the probability of generating a correct command for a fixed v' increases with increasing q/σ_N. Therefore, for a fixed noise level the input voltage must be set to within a fixed percentage of kq for a desired probability of obtaining a correct phase shifter command. For example, the input voltage must be set to within ±25% (±q/4) of kq for q/σ_N=10 to obtain a 99% probability of obtaining a correct command. It should be noted, however, that since the noise will be a function of optical intensity, the noise value used in the calculation should correspond to that which is expected under full optical illumination. Our measured value of q/σ_N=15 corresponds well with the experimental results.

CONCLUSION

Optical control of a six-bit X-band phase shifter requiring 310μW of optical power for 360° operation is demonstrated. The approach presented, applicable to any digital phase shifter regardless of operating frequency, is compatible with MMIC technology and parallel optical signal processing. The number of bits to which this technique may be extended is determined by both the noise of the optical link and the optical settability of the A/D input voltage. A quantitative expression is given for the probability of a correct phase shifter command under the assumption of additive Gaussian noise at the A/D input. This expression indicates a tradeoff between A/D quantization level, rms noise voltage, and the probability of issuing a correct (desired) digital command to the phase shifter. To increase the method to more bits or smaller A/D input ranges, the noise in the link must be reduced. This can be accomplished by replacing the LED with a high quality laser, replacing the multimode fiber with a single mode fiber, and improving the responsivity and linearity of the MESFET detector.

ACKNOWLEDGEMENT

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