An Active Phased Array With Optical Input and Beam-Scanning Capability

Siou Teck Chew, Tak Kit Tong, Ming C. Wu, and Tatsuo Itoh, *Fellow, IEEE*

***Abstract*— An active antenna array with optical input and beam scanning capability was developed. The phase shift between antenna elements is controlled by means of unilateral injection locking. The reference signal for injection locking is launched into optical fiber by a multiquantum–well InGaAs-InGaAsP distributed feedback laser. The RF signal is recovered by a photodetector at the other end of the link and fed to the RF circuit. Experimental result is presented and discussed.**

I. Introduction

IN RADAR, missile guidance, and communication system designs, engineers are constantly faced with the problem of limited space. In conventional systems, bulky amplifiers and motors are required to transmit high power and scan the antenna main beam, respectively. Waveguides is used for inter-connections since it has low loss and high power-handling capability. Being rigid, waveguide does not allow for conformity to the geometry of the space given. This constraint has led to continuing research in system and component designs to produce a highly integrated and compact design.

Lately, there is a growing interest in active antenna array, which integrates active subsystems with the antenna. Reports [1]–[3] have shown that transmitted power can be combined quasi-optically. It is also shown by previous authors [4]–[5] that the antenna main beam can be scanned electronically by introducing phase shift between adjacent antenna elements. An attempt was also made to control the phase shift optically [6].

In this paper, an attempt is made to solve the space problem by introducing a conceptual system configuration. In this system, not only microwave but optical active devices are integrated. It is designed to scan the main beam electronically using injection-locking oscillators. The reference signal is tapped from a stable source through an optical fiber link.

II. Design

The schematic system setup is shown in Fig. 1. The microwave reference signal for injection locking the phased array antenna is fed remotely through the optical fiber. The RF signal is first converted into optical signal by directly modulating a laser diode. The modulated optical signal is then launched into an optical fiber. The reference microwave signal is then recovered at the antenna through a high-speed photodetector and amplifier. Both the amplifier and photodetector are placed behind the array.

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The authors are with the Department of Electrical Engineering, University of California, Los Angeles, Los Angeles, CA 90024 USA.

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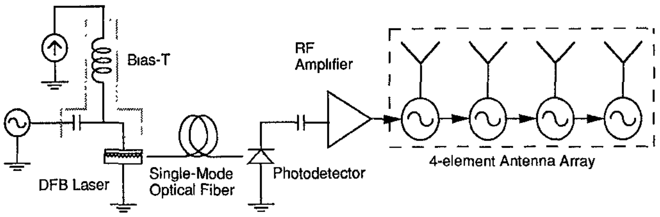

Fig. 1. Schematic diagram of the integrated optical input/phased array antenna.

A. Optical Circuit

A multiquantum–well (MQW) InGaAs-InGaAsP distributed feedback (DFB) laser, operating at 1.55-μm wavelength, is used for this work. The laser is index-guided by buried heterostructure and the active stripe width is 1 μm. The threshold current and external quantum efficiency of the DFB laser is 23 mA and 36.3 mW/A, respectively. Higher optical power can be obtained by properly adjusting the coupling strength of the DFB gratings. The 3-dB bandwidth of the laser is 10 GHz when biased at 100 mA. It has been shown that DFB laser has a better relative intensity noise (RIN) than Fabry-Perot laser and, therefore, better signal-to-noise ratio performance [7]. The DFB laser chip is mounted on an HP 83041C microcircuit package with wire bonding. The temperature is maintained at 15°C. A 4-dBm, 6-GHz RF signal of -10 dBm is pumped into the laser through a bias-tee. Light is collimated and focused by lenses into a standard single-mode fiber (SMF) with a core diameter of 9 μm. The average optical power in the SMF is -3.5 dBm when the laser is biased at 45 mA. The current modulation index is estimated to be 6.8%. A high-speed photodetector with a bandwidth of 34 GHz is used to detect and convert the optical signal into a RF signal. The photodetector is a p-i-n photodiode (HP 83440D). The expression for link efficiency is [8],

$$G = \frac{1}{R_L}\eta_{LB}^2 t_{od}^2 \eta_D^2 R_D$$

where R_L is the equivalent resistance of the laser diode above threshold, R_D is the photodiode's equivalent resistance, η_{LB} is the laser diode's slope efficiency, and t_{od} is the fiber's optical transfer efficiency. The overall insertion loss of the optical fiber link, including the coupling and detection loss, is measured to be -36 dB. This loss is due to low quantum efficiency of the laser and the impedance mismatch, which

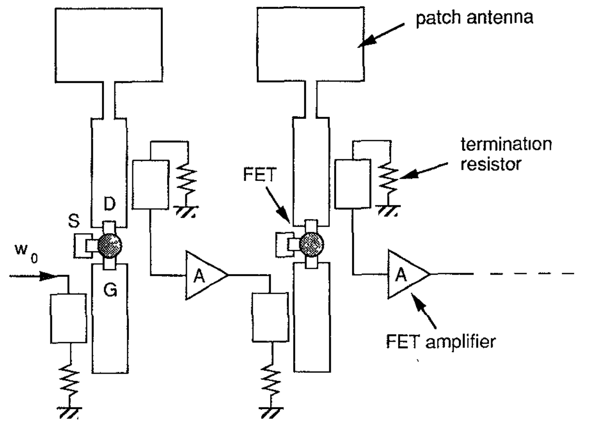

Fig. 2. Schematic diagram of the RF sub-circuit of the active antenna.

further reduces G by a factor of approximately 0.34. The link efficiency can be refined by improving quantum efficiency of the laser, input impedance matching, fiber coupling, and optical-RF conversion efficiency. An amplifier is used to boost the power level to 4 dBm for injection locking.

B. Four-Element Active Antenna Array

The design of the antenna array is based on Kurokawa's theory of injection locking [9]. A phase difference $\Delta\phi$ can be created between the oscillating signal and the injected signal and is related by the following equation:

$$\Delta\phi = \sin^{-1}\left(\frac{\omega_f - \omega_o}{\Delta\omega_m}\right), \tag{1}$$

where ω_f is the free-running frequency of the oscillator, ω_o is the injected signal frequency, and $2\Delta\omega_m$ is the locking bandwidth. The maximum phase difference is $\pm 90°$.

With this theory, injection-locking oscillators are designed. The schematic block diagram of the antenna array is shown in Fig. 2. The array consists of four rectangular microstrip patch antennae. Each antenna is fed by an oscillator, oscillating at about 5.8 GHz. The oscillators have 20-dB couplers at the gate and drain to inject and tap the power, respectively. The free-running frequency of the oscillators can be independently varied by changing the drain voltage of each oscillator. The choice of using drain bias as frequency control is a compromise between circuit complexity and performance.

When oscillator #1 receives the injected signal from the photodetector, it is locked to the injected signal frequency ω_o, and its phase is defined as ϕ_1. Similarly, oscillator #2 receives signal tapped from oscillator #1 and locked to ω_o with phase ϕ_2. The phase difference $\Delta\phi = \phi_2 - \phi_1$ obeys (1). This locking process is progressively established until all oscillators are locked. With the adjacent antenna radiating with phase difference $\Delta\phi$, the main beam can be scanned to an angle

$$\theta = \sin^{-1}\left(\frac{\lambda_0 \Delta\phi}{2\pi d}\right),$$

where λ_0 is the free space wavelength and d is the inter-spacing between adjacent antennae.

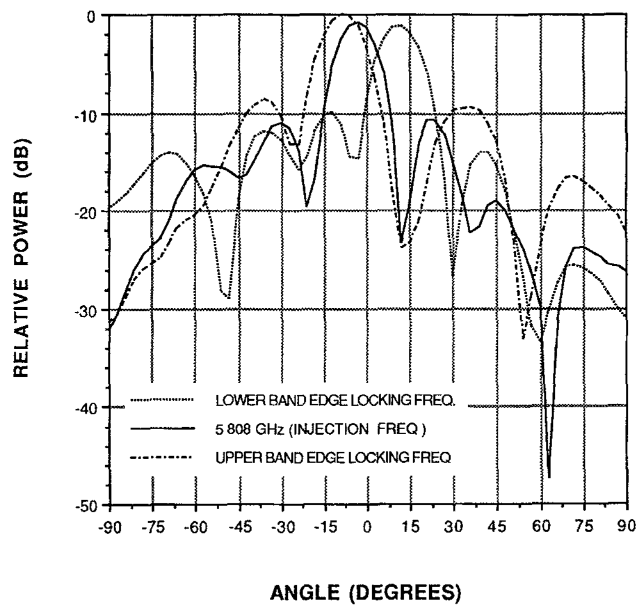

Fig. 3. Measured antenna pattern of the integrated active antenna array.

To prevent reverse injection locking, amplifiers with 25-dB isolation serve as active isolators between oscillators. The gain of the amplifiers and the coupling level of the couplers are considered for optimum locking bandwidth. The whole circuit is fabricated on a substrate with $\varepsilon_r = 2.33$. The circuit delay between two oscillators are designed to give a main beam at the broad side when $\Delta\phi = 0$. The antennae are placed 0.86 λ_0 apart so that mutual coupling through the antennae is kept minimal.

III. Results

With the system setup as shown in Fig. 1, the antenna pattern of the array is measured. The measured antenna pattern is shown in Fig. 3. With $d = 0.86\lambda_0$, the theoretical limit of the scan angle is 33°. With a frequency tuning range of 30 MHz, the measured scan angle is bout 21°. The scanned pattern is also asymmetrical. These discrepancies are due to difficulty in achieving band-edge injection locking, inconsistency in phase shift among antennae, and introduction of additional phase shift in the circuit layout. The difference in power level of the main beam is caused mainly by the varied drain voltages of the oscillators. The Effective Radiated Power (ERP) of this array is about 22.3 dBm. The array consumes 1.9 W of DC power, of which 1.5 W is from the amplifiers. The DC power consumption can be further reduced by using active isolators with lower gain.

IV. Conclusion

In this letter, an integrated active antenna system using optical input has been demonstrated. An unilateral injection locking active antenna array with electronic scanning capability has been designed. The reference injection signal is tapped from an optical photodetector. With the optical fiber link and active antenna system, space requirements can be greatly reduced. However, proper heat sinking and temperature-compensation control are required to reduce thermally induced frequency drift. The active antenna subsystem can be further improved to handle frequency mixing. Hence, the optical fiber link can transmit not only the reference signal but also modulated data signals.

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