A Compact Single Layer Injection-Locked Linear Scanning Array

Kenneth H. Y. Ip and George V. Eleftheriades

***Abstract*—A compact, single layer, CPW-fed, patch scanning array architecture using injection locking at 9.83 GHz is presented. The patch antennas are printed on the front side of the substrate while the electronics are situated at the back side leading to a simple and compact design. The unit element for the array is a self oscillating active patch antenna with a GaAs FET centered behind the patch for tight packing. The feedback for the oscillator is provided through electromagnetic coupling using a twin-slot arrangement behind the patch. A low power control signal is injected through parasitic coupling at the CPW side of the circuit. Phase shifting of the elements is achieved by electronically adjusting the gate voltage of the GaAs FETs. A scan range of −12°–9.5° is obtained for a four element prototype array.**

***Index Terms*—Active antennas, CPW, injection locking, patch antennas, phased arrays.**

I. INTRODUCTION

SCANNING antenna arrays utilizing injection-locked oscillators emerge as an attractive alternative to conventional phase-shifter based systems [1]. In these types of novel beam scanning arrays, the number of circuit power-dividers are reduced by utilizing active integrated antennas to achieve spatial power combining, which leads to reduced feed-line losses. In addition, the phase-shifters are replaced by injection-locked phase agile oscillators leading to a low cost design. Another added advantage is that the phase noise of the array can be lowered by using a low-power, stable reference oscillator. All of these attributes make these types of novel systems an attractive alternative for phased-array applications [1].

In this letter, the design of a low cost, compact, single layer linear scanning array using injection-locked active antennas at 9.83 GHz is presented based on CPW technology (see Fig. 1). The patch antennas are printed on the front side of the substrate while the electronics are situated at the back side of the substrate for a simple and compact design. With the patch antennas isolated from the electronics circuitry, good radiation characteristics are obtained.

II. ARRAY CONFIGURATION AND DESIGN

A. Configuration

The structure of the active antenna unit cell is based on the design presented in [2]. This unit cell features a simple and compact design, while maintaining good radiation characteristics. An expanded view of the active antenna element is shown in Fig. 2. As shown, the front side of the substrate hosts the patch whereas the active circuitry is accommodated at the back side in CPW technology. A Duroid 5870 substrate of $\varepsilon_r = 2.33$ with a thickness of 1.57 mm and an ATF-26 884 GaAs FET from Agilent Technologies are used in this design. For matching purposes, two open-circuited CPW stubs are used at the gate and the drain of the FET as shown in Fig. 2. For dc biasing, two discrete inductors and capacitors with $L = 5$ mH and $C = 47$ μF are soldered on the board with silver epoxy and are utilized as RF chokes, as also shown in Fig. 2. A four-element array is built using the active unit cell described previously (see Fig. 1). To feed the injection signal, a single 70 Ω CPW transmission line is employed as shown in Fig. 1. Series feed was chosen to distribute the injection signal in order to maintain a compact configuration (as opposed to a corporate feed requiring bulky power dividers). Furthermore, a 59.5 Ω quarter wavelength transformer is employed to match the 70 Ω line with the input 50 Ω CPW line and the external injection locking cable (see Fig. 1). On the other hand, coupling between the locking signal and the active antenna is achieved by connecting the injection signal line to the open-circuited stub at the gate of the FET using a pseudo-T-junction (see Figs. 1 and 2). In order to suppress the parasitic slot-line mode, air bridges are built on top of the CPW lines, especially around the pseudo-T-junction and the injection line. To maintain a zero phase difference of the injected signal among the active antennas, the length of the interconnecting CPW line between two adjacent patches is chosen close to one CPW wavelength λ_{CPW}. This corresponds to an inter-element

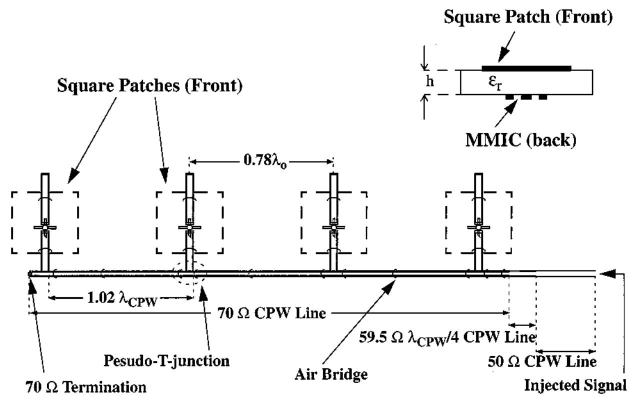

Fig. 1. Layout of the injection-locked array, $\varepsilon_r = 2.33$, $h = 1.57$ mm, $\lambda_{CPW} = 23.65$ mm, $\lambda_o = 30.52$ mm, 70 $\Omega CPW_{signal} = 1$ mm, 70 $\Omega CPW_{gap} = 0.2$ mm, 59.5 $\Omega CPW_{signal} = 1.2$ mm, 59.5 $\Omega CPW_{gap} = 0.1$ mm, 50 $\Omega CPW_{signal} = 1.26$ mm, 50 $\Omega CPW_{gap} = 0.07$ mm.

Manuscript received July 5, 2001; revised October 19, 2001. The review of this letter was arranged by Associate Editor Dr. Ruediger Vahldieck.

The authors are with the Edward S. Rogers Sr. Department of Electrical and Computer Engineering, University of Toronto, Toronto, ON, Canada (e-mail: ipkenne@waves.utoronto.ca; gelefth@waves.utoronto.ca).

Publisher Item Identifier S 1531-1309(02)00865-6.

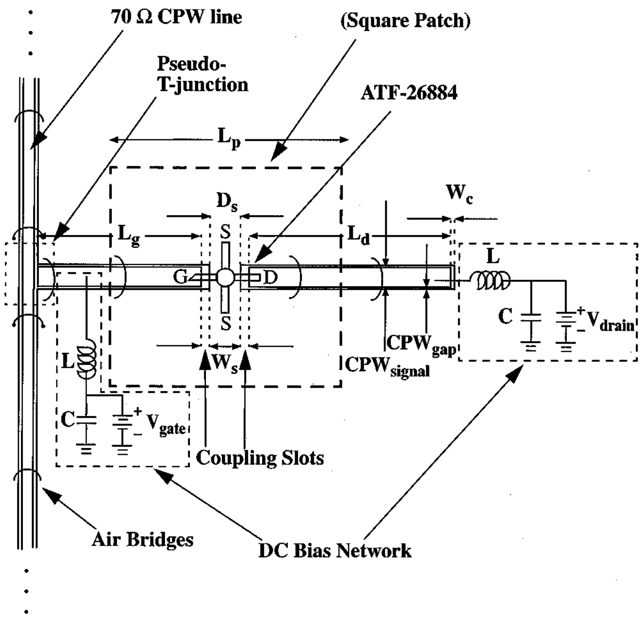

Fig. 2. Detailed layout of the active element, $L_p = 9.21$ mm, $L_g = 8$ mm, $L_d = 10.7$ mm, $W_c = 0.2$ mm, $W_s = 0.4$ mm, $D_s = 2.3$ mm, $CPW_{signal} = 2.3$ mm, $CPW_{gap} = 0.2$ mm, $L = 5$ mH, $C = 47$ μF.

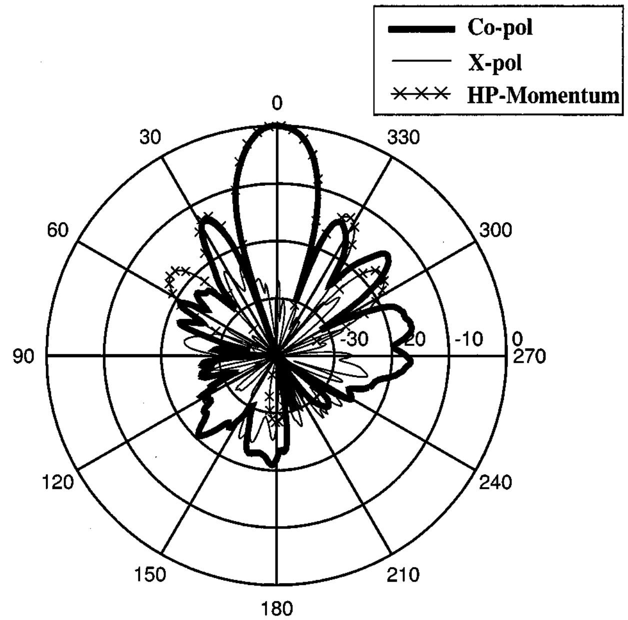

Fig. 3. Measured H-plane scan pattern of the array at broadside, $f = 9.83$ GHz.

spacing of roughly 0.78 free-space wavelengths λ_o. Due to the soldering tolerances and the S-parameters variation of the discrete GaAs FETs used, the active elements are tested individually for determining their free-running frequency range. A given FET is replaced with a new one if its free-running frequency range is not suitable. This procedure is repeated until a satisfactory frequency range is obtained for each FET.

B. Design

The oscillator design for each active element follows the procedure outlined in [2]. A new batch of ATF-26 884 GaAs FETs has been used for this design, which exhibits slightly different S-parameters than what was originally reported in [2]. Consequently, the dimensions of the active elements have been modified to compensate for this effect. The lengths and widths of the CPW stubs have been adjusted to yield a free running oscillation frequency of 9.83 GHz (see Fig. 2).

The design of this novel phased array is based on Adler's equation of injection locking [3]. When the injected signal locks with the free-running signal of the oscillator, a phase difference $\Delta\phi$ can be created between the oscillating signal and the injected signal and is related by the following equation

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

where ω_{inj} is the injected signal frequency, ω_o is the free-running frequency of the oscillator, and $2\Delta\omega_m$ is the locking bandwidth. According to theory, the maximum possible phase difference is $\pm 90°$.

From Fig. 1, the array is a series fed injection locking array similar to the ones described in [1]. The maximum progressive phase shift ($\Delta\Phi$) between two adjacent elements that can be achieved by this type of array is

$$\Delta\Phi(\max) = \frac{2\Delta\phi|_{\max}}{m-1} \tag{2}$$

where $\Delta\phi|_{\max} = 90°$ is the maximum phase difference between the oscillating signal and the injected signal, and $m \geq 2$ is the number of elements in the array. When the active elements are locked and radiate at the maximum progressive phase shift $\Delta\phi(\max)$, the corresponding maximum scanning angle for the array is

$$\theta_{\max} = \sin^{-1}\left(\frac{\lambda_0 \Delta\Phi(\max)}{2\pi d}\right) \tag{3}$$

where λ_0 is the free space wavelength and d is the antenna inter-element spacing. For the design of Fig. 1, $d = 0.78\lambda_o$ and $m = 4$, yielding a maximum progressive phase shift and a corresponding scanning range of $\Delta\Phi(\max) = \pm 60°$ and $\theta_{\max} = \pm 12.4°$, respectively.

III. Experimental Results

The active antenna patterns for each element have been tested in the anechoic chamber of the University of Toronto. A Wiltron 360SS69 sweep generator is used as the source for the control injection signal (see Fig. 1). The injection power presented to the input 50 Ω CPW line is −4.5 dB. The E- and H-plane radiation patterns and the phase noise of the elements have been individually measured and found similar to the ones reported in [2]. The measured EIRP for the single elements is, on average, 17.0 dBm.

Subsequently, the active radiation patterns of the array were measured and are reported in Figs. 3–5. The phase shifts for the

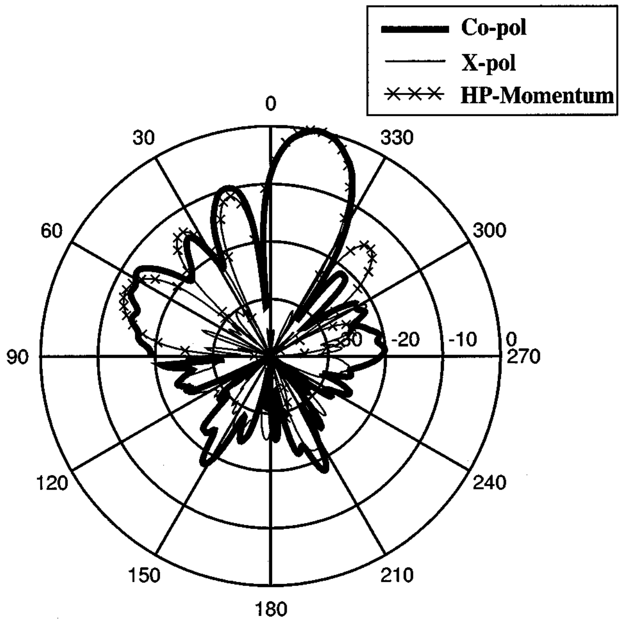

Fig. 4. Measured H-plane scan pattern at the "left" edge of the tuning range, $f = 9.83$ GHz.

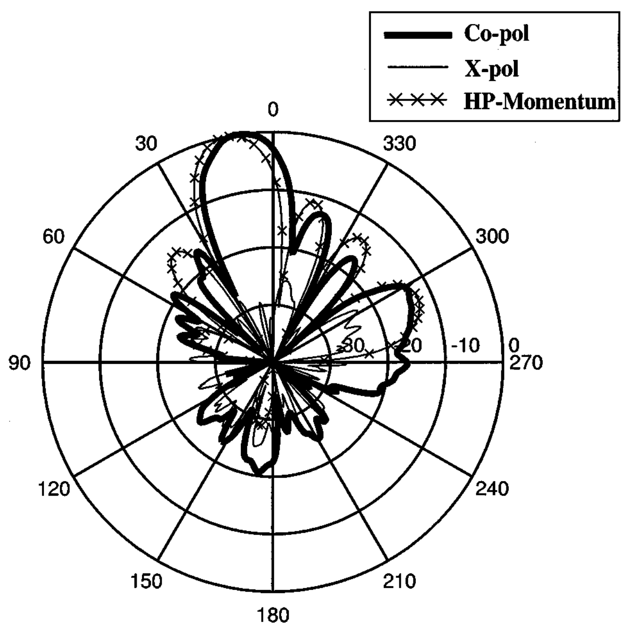

Fig. 5. Measured H-plane scan pattern at the "right" edge of the tuning range, $f = 9.83$ GHz.

active elements are achieved by varying the gate voltages of the GaAs FETs. A measured scan angle range from $-12°$–$9.5°$ has been observed as shown in Figs. 3–5. It is believed that the interconnecting feed-line is not exactly equal to 1 λ_{CPW} (see Fig. 1) and, thus, adds a constant phase shift to the antenna elements, resulting in an asymmetric scanning range. This 1.02 λ_o feed-line provides an extra $-7°$ phase shift to the antenna elements. From (3), the maximum progressive phase shifts among the antenna elements are calculated to be $\Delta\Phi(\max) = 53°$ and $-67°$. This leads to an asymmetric scan angle of $\theta_{\max} = 11°$ and $-13.8°$, which is in good agreement to the measured scan angle of 9.5° and $-12°$, respectively. On the other hand, the highest cross-polarization level of the array is found to be below 23 dB at broadside as shown in Figs. 3–5. Finally, based on the figure-of-merits defined in [4], the effective isotropic radiated power (EIRP) of the patterns in Figs. 3–5 have been measured to be 29.8 dBm ±0.5 dB, at an average dc bias condition of V_{drain} and I_{drain} of 3.5 V and 115 mA, respectively. From the measured radiation patterns, the directivity of the array is estimated to be $D = 15$ dB, resulting in an effective transmitter power, $P_{eff} =$ EIRP - D, of 14.8 dBm. These results for the single element and the array are summarized in Table I.

TABLE I
SUMMARY OF THE MEASURED CHARACTERISTICS OF THE SINGLE ELEMENT AND THE ARRAY

	Single Element (ave.)	Array (ave.)
f_{inj}	9.83 GHz	9.83 GHz
EIRP	17 dBm	29.8 dBm
D	8.3 dB	15 dB
P_{eff}	8.7 dBm	14.8 dBm

IV. SUMMARY AND CONCLUSION

In this letter, an injection-locked, phase-shifterless, beam scanning array architecture based on a compact, single layer, uniplanar unit-cell has been demonstrated. For a four-element prototype array, a maximum beam scanning range from $-12°$–$9.5°$ has been achieved which is in good agreement with the theoretical range of $-13.8°$–$11°$. This good agreement between the measured and predicted scan range demonstrates that apart from the size of the patches, the scan range is not limited by the size of the active unit cell. The tight packing nature of the proposed architecture makes it well suited for two-dimensional array implementations.

REFERENCES

[1] R. A. York and T. Itoh, "Injection- and phase-locking techniques for beam control," *IEEE Trans. Microwave Theory Tech.*, vol. 46, pp. 1920–1929, Nov. 1998.

[2] K. H. Y. Ip and G. V. Eleftheriades, "A compact CPW-based single layer injection-locked active antenna for array applications," *IEEE Trans. Microwave Theory Tech.*, vol. 50, Feb. 2002, to be published.

[3] R. Adler, "A study of locking phenomena in oscillators," *Proc. IEEE*, vol. 61, pp. 1380–1385, Oct. 1973.

[4] M. Gouker, "Toward standard figures-of-merit for spatial and quasioptical power-combined arrays," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 1614–1617, July 1995.