Application of Mutually Coupled Oscillators on Beam-scanning and Polarization-agile Antenna Array

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ABSTRACT

With the tunable relative phases, one-dimensional mutually coupled oscillator arrays have been used for the application of beam-scanning antenna arrays. In this paper, a two-dimensional mutually coupled oscillator array is studied for the application of a beam-scanning and polarization-agile antenna array. In the antenna array design, the polarization-agility is considered as one of the two dimensions (or *y*-direction) with the other dimension (or *x*-direction) for beam scanning of a two-dimensional oscillator array in *x-y* plane. By properly tuning the free-running frequencies of the oscillators, the array radiation direction can be scanned for the selected polarization states including linearly polarized, left-hand and right-hand circularly polarized states. The maximal phase difference of ±180° between coupled oscillating signals is acquired by using frequency doubling circuits. This then gives well-defined phase differences among oscillators for beam scanning in addition to the required quadrature phase difference for circular polarization. The performances of polarization agility and beam scanning for a four-element antenna array are verified experimentally.

I. INTRODUCTION

Mutually coupled oscillator array technique is known as an effective approach to yield the desired aperture phase distribution without phase shifters [1]. The operation principle of relative phase control is based on the injection-locking phenomenon of oscillators [2]. The phase relation between the injection signal and the oscillating signal of an injection-locked oscillator is described by the Adler's equation as [2]

$$\frac{d\phi}{dt} = \omega_o - \omega_{inj} - \frac{\varepsilon\omega_o}{2Q}\frac{A_{inj}}{A}\sin(\phi - \phi_{inj}), \tag{1}$$

where Q and ω_o are the quality factor and free-running frequency of the oscillator. A and ϕ are the amplitude and phase of the oscillating signal. A_{inj}, ϕ_{inj}, and ω_{inj} are the amplitude, phase, and frequency of the injection signal. $\omega_o - \omega_{inj}$ is the frequency detuning and $\Delta\omega = \varepsilon\omega_o A_{inj} / 2QA$ is the locking bandwidth.

For a coupled oscillator array operated under the nearest neighbor coupling condition, each oscillator is only affected by the adjacent oscillators, whose oscillating signals then become the injection signals. Therefore, a constant progressive phase can be achieved by detuning the free-running frequency of the edged oscillator elements [1]. In [3], it shows that a constant progressive phase distribution in a two-dimensional plane can also be acquired by properly detuning the edged oscillators of a two-dimensional oscillator array. One can then decompose this progressive phase distribution in *x-y* plane into *x*-direction and *y*-direction. By considering

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the polarization as one of the two dimensions (for example, y-direction), an antenna array is designed in this paper to be a one-dimensional (x-direction) beam-scanning antenna array with polarization-agile capability.

From (1), the maximal phase difference is limited to ±90° within the locking bandwidth. For generating a circular polarization wave, this phase difference is critically satisfied at the locking margin and the locking condition tends to be unstable. To obtain a wider phase difference range, frequency multiplying approach is used to enhance the scanning angle [4]. In other words, the frequency doubling is utilized to extend oscillator tunable phase difference to be ±180°. This then allows a stable beam-scanning and polarization-agile operation by detuning the free-running frequencies of a two-dimensional oscillator array.

II. PRINCIPLE

Figure 1 is the block diagram of the developed beam-scanning and polarization-agile antenna array. For an N-element antenna array, 2N oscillators are divided into horizontal polarization row (or H-row) and vertical polarization row (or V-row), since in each antenna element, two oscillators are arranged to generate the corresponding polarizations. All the oscillators have the free-running frequency near ω_o, and the patch antennas are resonated at the second-harmonic frequency $2\omega_o$. The coupling between two adjacent oscillator elements is achieved by an external resistive coupling network. The oscillator is designed as an oscillating doubler by properly biasing the transistor and matching the output to the patch antenna at $2\omega_o$.

Applying (1) to a two-dimensional oscillator array, the phase distribution of the 2N frequency-doubled oscillating signals in H-row, $\phi_{1,1}, \phi_{2,1}, \cdots, \phi_{N,1}$, and V-row, $\phi_{1,2}, \phi_{2,2}, \cdots, \phi_{N,2}$ satisfy

$$\begin{cases} \dfrac{1}{2}\dfrac{d\phi_{1,1}}{dt} = \omega_{o,1,1} - \omega - \dfrac{\omega_{o,1,1}}{2A_{1,1}Q_{1,1}}\left[\varepsilon_x A_{2,1}\sin(\dfrac{\phi_{1,1}-\phi_{2,1}}{2}) + \varepsilon_y A_{1,2}\sin(\dfrac{\phi_{1,1}-\phi_{1,2}}{2})\right] \\ \dfrac{1}{2}\dfrac{d\phi_{1,2}}{dt} = \omega_{o,1,2} - \omega - \dfrac{\omega_{o,1,2}}{2A_{1,2}Q_{1,2}}\left[\varepsilon_x A_{2,2}\sin(\dfrac{\phi_{1,2}-\phi_{2,2}}{2}) + \varepsilon_y A_{1,1}\sin(\dfrac{\phi_{1,2}-\phi_{1,1}}{2})\right] \end{cases}$$

$$\begin{cases} \dfrac{1}{2}\dfrac{d\phi_{n,1}}{dt} = \omega_{o,n,1} - \omega - \dfrac{\omega_{o,n,1}}{2A_{n,1}Q_{n,1}}\left[\varepsilon_x A_{n-1,1}\sin(\dfrac{\phi_{n,1}-\phi_{n-1,1}}{2}) + \varepsilon_x A_{n+1,1}\sin(\dfrac{\phi_{n,1}-\phi_{n+1,1}}{2}) \right. \\ \left. + \varepsilon_y A_{n,2}\sin(\dfrac{\phi_{n,1}-\phi_{n,2}}{2})\right] \\ \dfrac{1}{2}\dfrac{d\phi_{n,2}}{dt} = \omega_{o,n,2} - \omega - \dfrac{\omega_{o,n,2}}{2A_{n,2}Q_{n,2}}\left[\varepsilon_x A_{n-1,2}\sin(\dfrac{\phi_{n,2}-\phi_{n-1,2}}{2}) + \varepsilon_x A_{n+1,2}\sin(\dfrac{\phi_{n,2}-\phi_{n+1,2}}{2}) \right. \\ \left. + \varepsilon_y A_{n,1}\sin(\dfrac{\phi_{n,2}-\phi_{n,1}}{2})\right] \end{cases}$$

$$\vdots$$

$$\begin{cases} \dfrac{1}{2}\dfrac{d\phi_{N,1}}{dt} = \omega_{o,N,1} - \omega - \dfrac{\omega_{o,N,1}}{2A_{N,1}Q_{N,1}}\left[\varepsilon_x A_{N-1,1}\sin(\dfrac{\phi_{N,1}-\phi_{N-1,1}}{2}) + \varepsilon_y A_{N,2}\sin(\dfrac{\phi_{N,1}-\phi_{N,2}}{2})\right] \\ \dfrac{1}{2}\dfrac{d\phi_{N,2}}{dt} = \omega_{o,N,2} - \omega - \dfrac{\omega_{o,N,2}}{2A_{N,2}Q_{N,2}}\left[\varepsilon_x A_{N-1,2}\sin(\dfrac{\phi_{N,2}-\phi_{N-1,2}}{2}) + \varepsilon_y A_{N,1}\sin(\dfrac{\phi_{N,2}-\phi_{N,1}}{2})\right] \end{cases} \quad (2)$$

All the coupling phases among oscillators are designed to be zero. ε_x and ε_y are the coupling coefficients in x–direction and y–direction, respectively. $\omega_{o,n,p}$, $Q_{n,p}$ and $A_{n,p}$ are the free-running frequency, quality factor and the oscillating amplitude of the (n,p)th oscillator element. Here, n denotes the index in x-direction (or antenna element index) and p denotes the row index (or polarization index). For anti-symmetric frequency detuning, the synchronized frequency ω is equal to the average of the 2N free-running frequencies $<\omega_{o,n,p}>$ [3]. Note all the signal phases are divided by 2 compared to (1) due to the frequency doubling used.

It is known that detuning the edged oscillator elements controls the constant progressive phase of a two-dimensional coupled oscillator array [3]. In Fig. 1, all the 2N oscillators are edged elements to be detuned in the operation. Note (2) shows that the phase controls are independent in x-direction and in y-direction, therefore, the 2N frequency detuning parameters can be reduced to two parameters, $\Omega_x = (\omega_{o,1,p} - \omega)/\Delta\omega_x = -(\omega_{o,N,p} - \omega)/\Delta\omega_x$ and $\Omega_y = (\omega_{o,n,1} - \omega)/\Delta\omega_y = -(\omega_{o,n,2} - \omega)/\Delta\omega_y$, which are the frequency detunings in x-direction and in y-direction respectively.

A typical two-dimensional frequency detuning and its corresponded phase distribution are shown in Fig. 2 and Fig.3 by assuming $\Delta\omega_x$=$\Delta\omega_y$. The corresponded beam-scanning angle becomes

$$\theta = \sin^{-1}(\frac{\Delta\phi_x \lambda}{d}) = \sin^{-1}[\frac{2\lambda}{d}\sin^{-1}(\frac{\Omega_x}{\Delta\omega_x})], \tag{3}$$

where d is the spacing of antenna elements in x-direction and λ is the wavelength in free-space. The radiation polarization is then

$$\overline{E} = \hat{x} + e^{j\Delta\phi_y}\hat{y} = \hat{x} + e^{j2\sin^{-1}(\frac{\Omega_y}{\Delta\omega_y})}\hat{y}, \tag{4}$$

as a patch antenna is connected to two oscillators in y-direction. Equations (3) and (4) show that the parameter Ω_x controls the beam-scanning angle, whereas Ω_y controls the radiation polarization.

III. RESULTS

A four-element beam-scanning and polarization-agile antenna array is designed in this paper. The oscillating doubler is implemented with transistor NE32684A and varactor diode BB131. A typical calculated and measured radiation pattern of the designed antenna array for a right-hand circularly polarizated wave with scanning angle 13° is shown in Fig. 4. The cross-polarized component is shown with more than 10 dB below the co-polarized component.

IV. CONCLUSION

In this paper, the formulations of a beam-scanning and polarization-agile antenna array using a two-dimensional mutually coupled oscillator array are developed. Through the use of frequency doubling, the phase difference between coupled oscillating signals is extended to ±180° for the proper polarization and oscillator operations. A one-dimensional beam-scanning and polarization-agile antenna array is demonstrated at 6 GHz.

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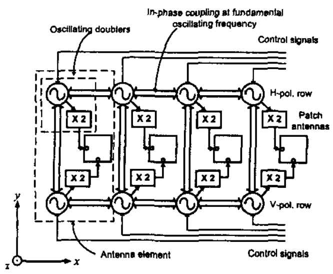

Fig.1 Block diagram of a four-element beam-scanning and polarization-agile antenna array.

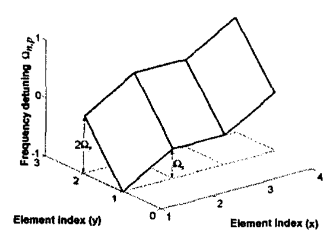

Fig.2 Frequency detuning of the oscillator array for a right-hand circularly polarized wave at 13° beam-scanning angle.

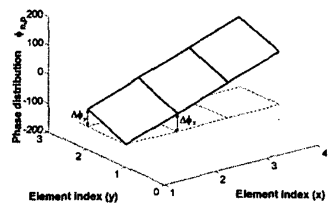

Fig.3 Calculated phase distribution of the oscillating doublers.

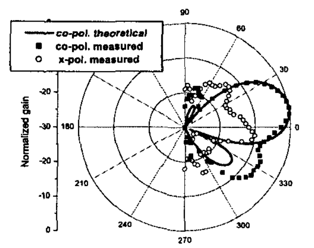

Fig.4 Calculated and measured RHCP radiation pattern of a four-element antenna array.