行政院國家科學委員會專題研究計畫　成果報告

無線接取技術之關鍵元組件子計畫一：注入鎖定技術之研究

(3/3)

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行政院國家委員會專題研究計畫成果報告

無線接取技術之關鍵元組件 子計畫一：注入鎖定技術之研究(3/3)

Research on injection-locking technology (3/3)

計畫編號：NSC91-2219-E-002-030
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一、 中文摘要

本計畫旨在建立注入鎖定技術於無線接取關鍵元組件之應用，以及相關之主動天線陣列之理論分析、模擬與實驗量測，此外並協助各子計畫進行無反射室設備之改建與擴充。

本報告係敘述第三年之研究成果，主要敘述注入鎖定技術應用於波束-極化掃描主動天線陣列之理論分析、模擬與實驗量測，以及注入鎖定天線陣列之耦合理論分析、模擬。

關鍵詞：注入鎖定、波束-極化掃描、天線陣列耦合。

英文摘要

The purpose of this three-year research project is to develop the basic theory, numerical simulation and experimental measurement of the key components using injection locking technology in the applications of wireless access system. In addition, this project will continue supporting the improvement of the anechoic chamber facility which is the major measurement environment for the antennas involved in all the related subprojects.

In this third-year report, the study results are mainly focused on the development of a novel beam-scanning and polarization-agile active antenna array using injection locking technology, and theoretical analysis of injection-locked antenna array (ILAA) including mutual coupling effects.

Key words: injection locking technique, beam-scanning and polarization-agile active antenna array, mutual coupling effects.

二、 計畫緣由與目的

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]

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

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 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.

In this year, the scattering and radiating analysis of dipole antenna array with each element loaded with a two-terminal oscillator is also studied. The active antenna array is illuminated by an external injection plane wave. Since all the equivalent exciting sources at each antenna terminal are in coherence, the injection-locked antenna array is synchronized to injection signal frequency. The analysis is then equivalent to solving a multiport network circuit with each port in shunt with a two-terminal oscillator and an equivalent exciting source. The multiport network parameters of antenna element are obtained by the moment method. Since it is difficult to achieve an analytic time domain model of oscillator, another approach different from that given for analyzing passive nonlinear load case is proposed to solve the resulting equivalent multiport network circuit.

三、研究方法及成果

I. Beam-scanning and Polarization-agile Antenna Array

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, $\phi_{1,1}, \phi_{2,1}, \Lambda, \phi_{N,1}$, and V-row, $\phi_{1,2}, \phi_{2,2}, \Lambda, \phi_{N,2}$ satisfy

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

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

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

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

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

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

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

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.

II. Array implementation

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.

III. Mutual coupling analysis of injection-locked antenna array

In the formulation, the injection locking performance analysis of dipole antenna array, as shown in Fig.5, with each element loaded with a two-terminal oscillator is developed. The analysis is based on the nonlinear model of oscillator and the linear model of antenna array considering mutual coupling effects. The locking range of injection signal and the array radiating power are obtained by solving an equivalent multiport network. In general, the solutions include stable and unstable solutions. The Routh-Hurwitz stability criterion is then applied to remove the unstable solutions.

IV. Simulation

In the simulation, dipole antenna is of length 10 cm and diameter 0.135 cm. It is loaded with a two-terminal oscillator. Numerical results show that the array performance such as frequency locking range, radiation power by taking into account the array mutual coupling effects is quite different from those of an isolated antenna element. In addition, the influence of antenna element spacing upon array locking parameters in this study is found to be consistent with other existing theories [5]. Fig.6 shows the frequency locking range (as the shadow region) of the two-dipole ILAA under different dipole spacing. It also shows that different array geometries have different mutual coupling effects and thus lead to different frequency locking ranges.

四、結論與討論

In this study, 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.

In addition, the locking performance of injection-locked antenna array is analyzed with the consideration of array mutual coupling effects. The analysis is formulated in the frequency domain because the nonlinear characteristics of oscillator is given in the frequency domain. A characteristic equation with the power of $2N$ is derived to describe the stable condition of an N-element injection-locked antenna array. The Routh-Hurwitz stability criterion is then applied to verify the stability property of each possible solution. Numerical simulation results show that the array performance by taking into account the array mutual coupling effects is quite different from that of an isolated antenna element. The array locking range is shifted as there exists strong array mutual coupling effect, however, the array locking bandwidth is almost unchanged. The analysis given in this paper is useful in the application of ILAA in the areas of communication system and remote sensing.

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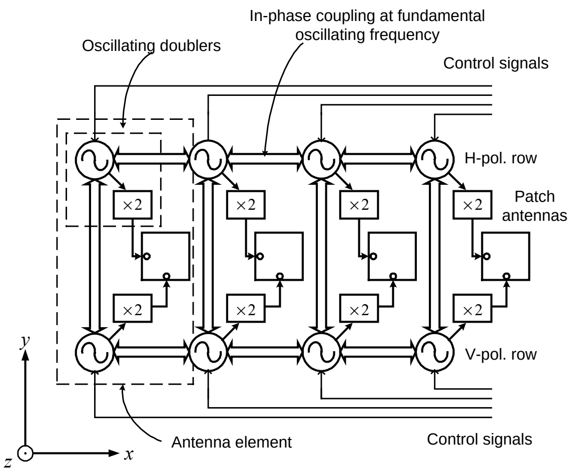

Fig.1 Block diagram of a four-element beam-scanning and polarization-agile antenna array.

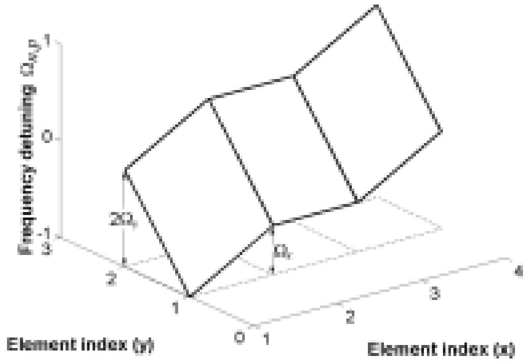

Fig.2 Frequency detuning of the oscillator array for a right-hand circularly polarized wave at 13° beam-scanning angle.

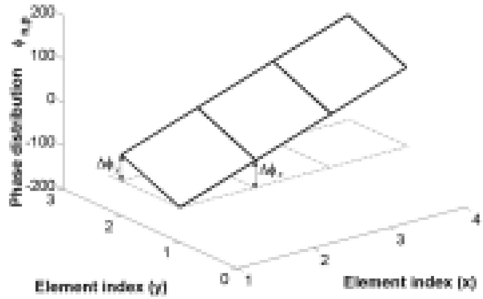

Fig.3 Calculated phase distribution of the oscillating doublers.

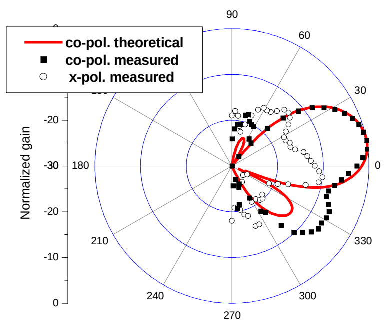

Fig.4 Calculated and measured RHCP radiation pattern of a four-element antenna array.

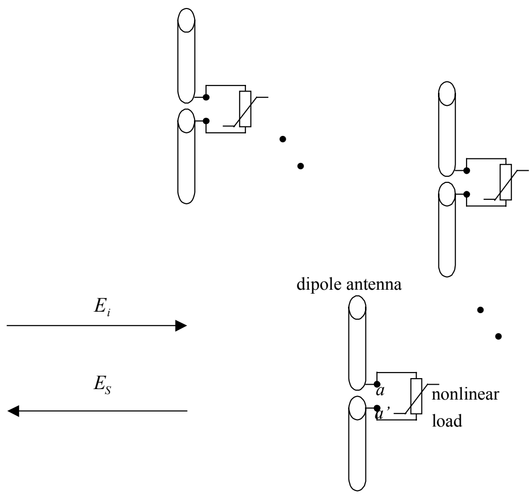

Fig.5 Schematic diagram of an injection-locked dipole antenna array.

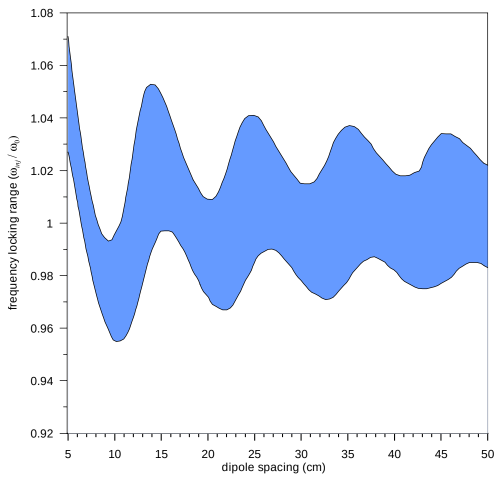

Fig.6 The frequency locking range of a two-dipole ILAA described above for different dipole spacing.