UNILATERALLY COUPLED ACTIVE ANTENNA ARRAY CONTROLLED BY VARACTOR DIODE

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1. Introduction

Recently, arrays of microwave and millimeter wave antennas each mounted with an active device have received much attention for spatial power combining to obtain high power solid–state sources and for electronic beam scanning[1]. As a phased array method using such active antennas, one–dimensional unilaterally coupled oscillator arrays were proposed[2]-[5]. The electromagnetic wave can be scanned by controlling the free–running frequencies of the oscillators. As a method for tuning the frequency of the oscillator, the bias voltages applied to the active devices were controlled. However, the tuning range is not very wide, and there is the fear of which the scan range of the radiated wave is limited for the reason. All oscillators may not be synchronized for the deviation of the free–running frequencies of the oscillators. The active antenna mounted with a varactor diode was reported[6] though the antennas were bilaterally coupled. Because the varactor was embedded in a patch antenna, adverse effect may be given in the radiation characteristics when the resonant frequency of the patch antenna is varied by controlling the bias voltage applied to the varactor.

In this paper, we investigate a phased array behavior using unilaterally coupled active antennas which consist of an oscillator mounted with the varactor diode and a patch antenna.

2. System configuration

Figure 1 shows a configuration of a unilaterally coupled active antenna array. The active antenna is composed of a two–port oscillator with the unilateral characteristics and an antenna. N two–port oscillators and an oscillator as an injection signal source are mutually coupled with coupling strength β. The coupling phase between the neighboring oscillators are chosen to be an integral multiple of 2π, so that each oscillator operates in–phase when the free–running frequencies of all oscillators including the oscillator #0

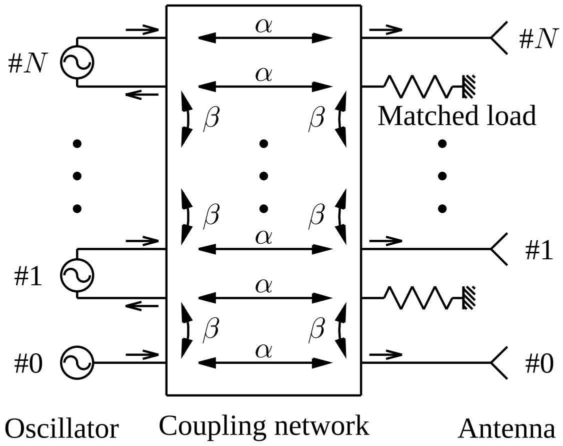

Fig. 1: Configuration of unilaterally coupled active antenna array

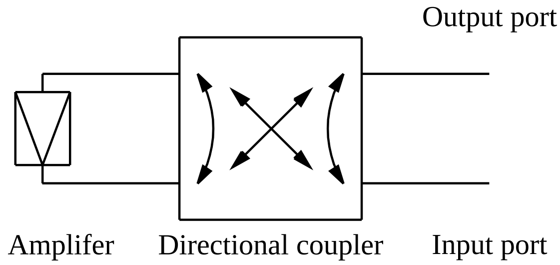

Fig. 2: Two–port oscillator

are the same. The output power of each oscillator is radiated from each antenna through the main line (transmission coefficient α) of the coupler. Figure 2 shows a composition of the two–port oscillator which consists of an amplifier and a directional coupler for feedback to the amplifier and output of the generated power. The oscillator operates at the frequency in which the electrical length of the feedback loop becomes an integral multiple of 2π. If the input and the output ports of the amplifier are matched and the reverse gain of the amplifier is equal to zero, the oscillated power is output only at the output port of the oscillator and is not output at the input port, and only the signal injected from the input port affects the operation of the oscillator, so that the two–port oscillator has the unilateral characteristics. Though the oscillator are coupled using the bi–directional coupler, unilateral coupling can be realized. Thus, all the oscillators are injection–locked sequentially from the oscillator #1 to the oscillator #N. When the free–running frequencies of the oscillator #1 to #N are shifted from the oscillation frequency f_0 of the oscillator #0 to $f_0 + \Delta f$, the phase differences between adjacent oscillators take a uniform value $\Delta\phi$ as

$$\Delta\phi = \sin^{-1}\left(\frac{Q_{\mathrm{ex}}\Delta f}{\beta f_0}\right)$$

where Q_{ex} is the external quality factor of the two–port oscillator and the array operates at the frequency f_0[4]. At $\Delta f = \frac{\beta f_0}{Q_{\mathrm{ex}}}$, the synchronization reaches a limit and the phase difference $\Delta\phi$ can be varied up to $\frac{\pi}{2}$.

3. Oscillator controlled by varactor

We fabricated the two–port oscillator as shown in Fig.3. An FET as the amplifier and a hybrid coupler as the directional coupler for feedback were used. A varactor diode is connected with the feedback loop in parallel. In order to change the free–running frequency of the oscillator, a gate–source bias voltage V_{GS} and a drain–source bias voltage V_{DS} of the FET and a bias voltage V_{v} applied to the varactor diode were controlled because the transmission phase of the place of the FET changes by V_{GS} and V_{DS} and the transmission phase of the place of the varactor diode changes by V_{v}. The DC bias voltages were applied through bias lines with radial chokes. The feedback loop had three chip capacitors of 3pF in order to shut out DC bias voltages from other circuit elements.

The oscillator was fabricated on Rogers Duroid 5870 substrate with a thickness of 0.51mm and relative dielectric constant of 2.33. The oscillation characteristics of the fabricated oscillator versus the bias voltage was measured. Figure 4 shows a typical variation of the oscillation frequency and the output power with V_{v} and V_{GS} when $V_{\mathrm{DS}} = 5$[V]. The oscillation frequency was tuned largely by changing the bias voltage V_{v} of the varactor compared with changing of the gate–source voltage V_{GS}. It is possible that the output power should not change very much and that the oscillation frequency is made to change by the gate–source voltage V_{GS} of the FET and the bias voltage V_{v} of the varactor. The oscillated power is output almost at the output port of the oscillator, so it is considered that the oscillator had the unilateral characteristics.

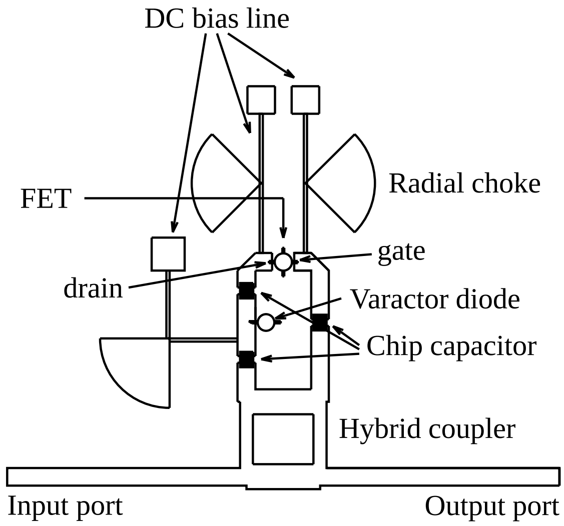

Fig. 3: Fabricated two–port oscillator controlled by varactor diode

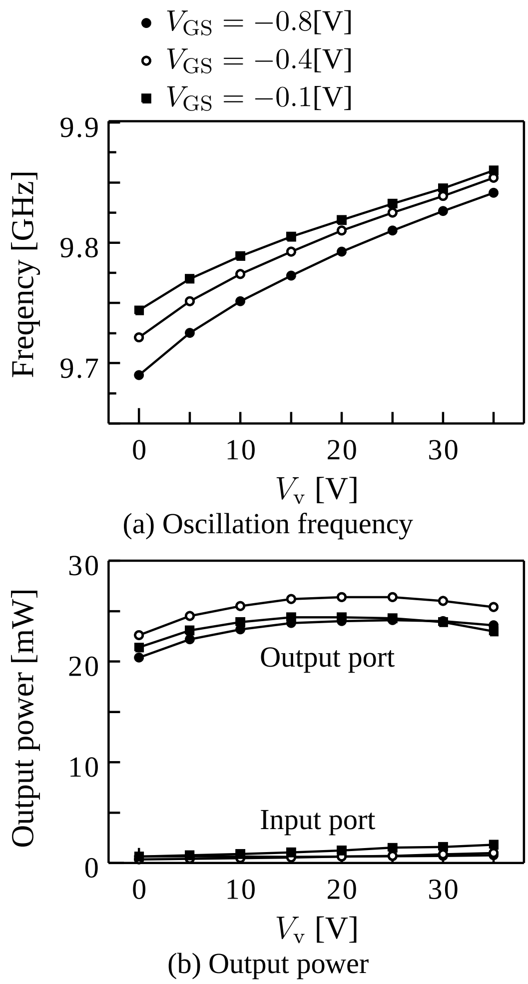

Fig. 4: Oscillation characteristics of the fabricated two–port oscillator when $V_{\mathrm{DS}} = 5$[V]

4. Experiment of beam scanning

An experiment of beam steering using active antenna array as shown in Fig.5 was carried out. A patch antennas were used in order to radiate the oscillated power and were placed on H–plane. The directional coupler for coupling the oscillators was inserted between the oscillator and the patch antenna. An isolator was inserted between the oscillator #0 and the coupler in order not to be injected the signal from the oscillator #1 to the oscillator #0. The input ports of the two–port oscillators were matched by inserting a chip resistor of 50Ω at the position quarter–wavelength away from the open termination. A center–to–center spacing between the adjacent patch antennas was 25mm, which corresponds to about 0.8 times of the wavelength in free space. The length of the coupling line was determined experimentally so that the electromagnetic wave may be radiated in the direction of broadside when the free–running frequencies of all the oscillators were the same.

The result of the experiment using five antenna array $(N = 4)$ is shown as follows. Figure 6 shows the radiation patterns on H–plane of the five antenna elements which were individually measured at the same frequency of 9.71GHz, where the output power of the oscillator #0 was 24.5mW. The radiated power was received by a rectangular horn antenna 1.5m away from the active antenna array. The patterns of the five antennas deviated due to the undesired radiation from other circuit elements. The radiated beam from the five antenna array was scanned by giving the frequency change Δf to the active antenna #1 to #N by controlling V_{v} and V_{GS} when the oscillation frequency of the oscillator #0 was fixed at $f_0 = 9.71$[GHz]. The measured radiation pattern on H–plane was shown in Fig.7 when the frequency change Δf was equal to zero and was changed to the end of the locking range. In the case of $\Delta f = 0$, the radiated power from the five antennas was successfully combined in the broadside direction though the grating lobe was appeared when $\Delta f = -42$[MHz], because the spacing between antennas was wider than half of the wavelength. Maximum received power of the main lobe reduced when the electromagnetic wave scanned from the broadside direction. This is because the gain of the individual patch antenna decreases as the radiation direction separates from broadside and the phase differences between the adjacent antennas deviate as the frequency change Δf increase. Figure 8 shows the scan angle versus the frequency change Δf. The electromagnetic wave scanned form $-13.6°$ to $+12.6°$. It corresponds to the variation of the phase differnce between the neighboring antennas from -0.38π rad to $+0.36\pi$ rad. That the phase difference did not reach 0.5π rad is due to the deviation of the oscillation characteristics, especially the free–running frequency, of the individual active antenna.

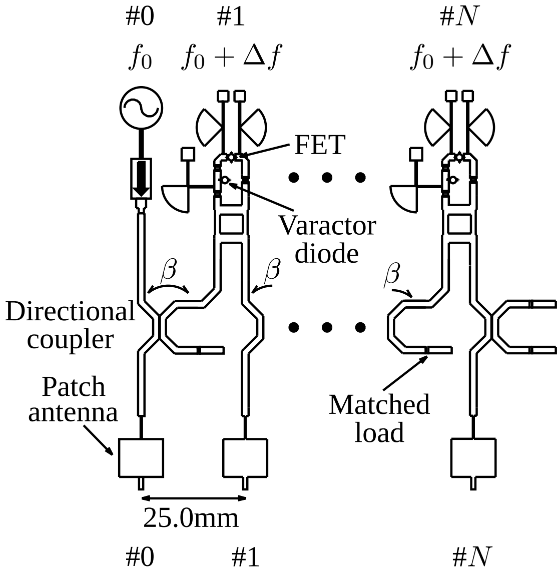

Fig. 5: Unilaterally coupled active antenna array

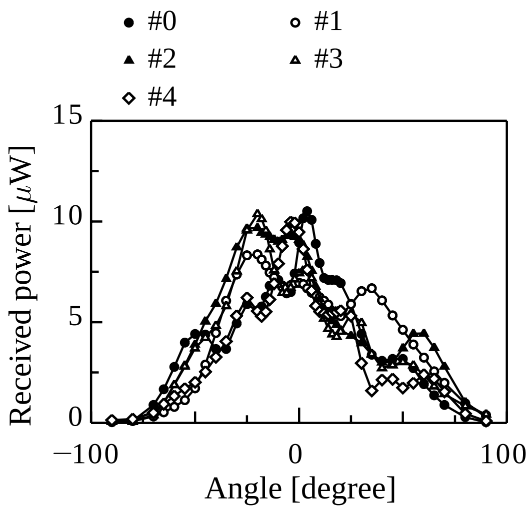

Fig. 6: Radiation patterns on H–plane of the antenna elements

5. Conclusion

An approach to the unilaterally coupled active antenna array controlled by the varactor diode has been presented. The active antenna consists of the patch antenna and the two–port oscillator with the unilateral characteristics. By mounting the varactor diode in the oscillator, it was shown that the oscillation frequency can be changed more

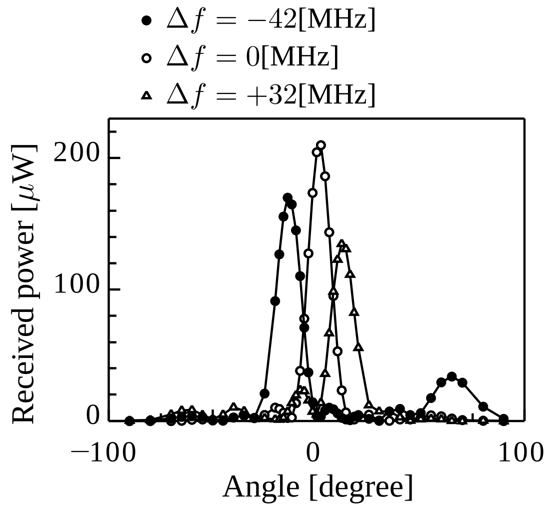

Fig. 7: Measured radiation pattern on H–plane of the five antenna array

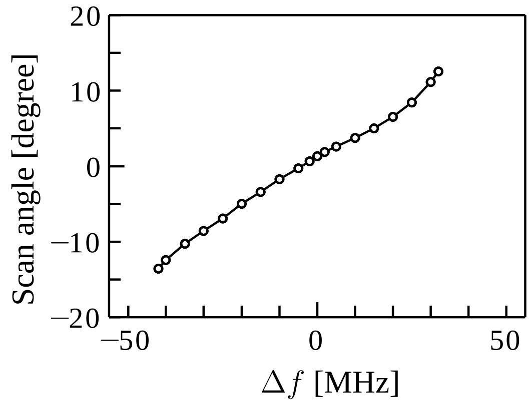

Fig. 8: Scan angle versus the frequency change Δf

largely. In the experiment using the five element array, the radiated beam was scanned to the end of the locking range by controlling the bias voltage of the varactor diode. Beam scanning using many more antennas and in higher frequency range will be future subjects.

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