A Novel K-band Frequency-Controlled Beam-Steering Quasi-Yagi Array with Mixing Frequency Compensation

Takahide Nishio, Yuanxun Wang, Yongxi Qian, and Tatsuo Itoh

Department of Electrical Engineering, University of California Los Angeles, Los Angeles, CA, 90095, U.S.A.

***Abstract* — A new type of compact K-band frequency-controlled beam-steering array utilizing fixed progressive delay lines in combination with passive double-balanced MMIC mixers integrated with quasi-Yagi antenna elements is presented. The beam steering is carried out by simply changing the frequency of the LO and IF signals at the same time such that the radiation frequency keeps constant. The K-band (20 GHz) four-element array fabricated on the Alumina substrate demonstrates 40 degree scanning with an LO frequency change from 22 to 26.2 GHz by the short delay lines installed in the LO line and ensures broadband data transmission with well-defined radiation patterns.**

I. INTRODUCTION

A simple and cost-effective beam-forming scheme is a highly desirable component of any transmitter/receiver system. One of the simplest ways to accomplish beam steering is by simply changing the RF frequency to adjust the phase shifts presented by fixed delay lines. Such a scheme eliminates the need for expensive phase shifter components. The radiation frequency can be kept constant by balancing the frequency changes between the LO and IF signals. An X-band phased array antenna using this concept is introduced in [1]. In that scheme, in order to eliminate the beam squinting caused by the signal modulation, the modulated signal is applied to the LO port which simultaneously pumps mixers at the same time.

In this paper, a K-band frequency-controlled beam-steering quasi-Yagi array is proposed to utilize the vast spectrum resources available for broadband data at higher frequency bands. Instead of modulating the LO, the modulated signal is applied to the IF input and the fixed delay lines are employed to the LO. Compared to the scheme proposed in [1], the amplitude variation at the RF output due to the loss of the delay lines is minimized. This happens because the conversion gain of the mixer shows a flat response near the point of optimum pumping power. This leads to better radiation patterns and eliminates signal distortion due to the large signal drive since the modulation occurs IF. Moreover, the beam squint associated with the frequency-shift for typical frequency scanning arrays can be avoided because there is no phase delay lines at the IF line. When combined with the broadband characteristics of the quasi-Yagi antenna, high data rate operation can be realized.

This paper is organized as follows. First, the system operation principles are introduced and the circuit overview is given. Then the design issues of each component in the system are discussed. Finally, the measured results are presented as a validation of the system performance.

II. CIRCUIT OVERVIEW

Figure 1 shows a K-band prototype of the newly proposed beam-steering array fabricated on a 10-mil thick Alumina substrate with a dielectric constant of 9.8. The wide bandwidth afforded by the quasi-Yagi antenna [2-4] makes possible broadband signal transmission in this new type of beam steering array. The low profile of the quasi-Yagi antenna element leads to a compact layout of the entire scanning array (2 by 2.7 inches) which integrates MMIC chip mixers [4]. Wire-bonds for the IF feed lines are used to cross over the LO feed lines and to connect surface-mounted MMIC mixers. This results in a one-sided layout that offers easy fabrication and allows the implementation of the bias network on the back side (at ground plane). Two input feed lines (LO and IF) connect to the MMIC mixers. The IF line consists of a corporate feed of equal power, equal phase power dividers feeding the IF port of each mixer. The LO line consists of parallel equal power dividers with fixed delay lines in order to feed a large power signal of equal amplitude but uniformly progressive phase delay to each LO port of the mixer. Each length of the fixed delay line installed in the LO line is carefully designed so that two neighboring phase delay becomes a multiple of 2π to provide a broadside radiation at the center frequency f_0 of the LO carrier. The necessary phase shift for each element for beam steering is therefore created in the LO line by simply changing the LO frequency. The frequency of the IF signal is changed at the same time as the LO frequency changes so that the radiation frequency is kept in constant value at f_{rad}, while the necessary scanning is implemented. Passive double-

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balanced diode mixers are utilized for mixing to the fixed radiation frequency to each antenna element.

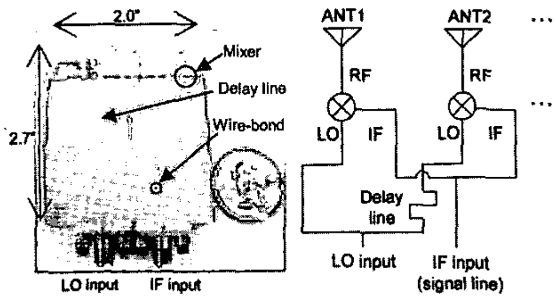

Fig.1 K-band frequency-controlled beam-steering quasi-Yagi array.

The mixing operation shown in Figure 2 is implemented in the following manner. For uniform arrays, the normalized array factor AF_n is known as:

$$AF_n = \frac{\sin\left(N\frac{\Psi}{2}\right)}{N\sin\left(\frac{\Psi}{2}\right)} \quad (1)$$

where $\Psi = kd\cos\theta + \alpha$, N is the number of elements, k is the propagation constant in free space, d is the element spacing, and α is the phase delay of the delay line between neighboring elements. Thus, for the element spacing $d = \lambda_{rad}/2$, the required phase delay α is:

$$\alpha = -kd\cos\theta = -\pi\cos\theta \quad (2)$$

where λ_{rad} is the free space wavelength at the radiation frequency f_{rad}, and θ is the scan angle. To have a broadside radiation at the center frequency f_0 of the LO carrier, the phase delay of the delay line between neighboring elements must be set at:

$$\alpha(f_0) = \frac{2\pi l}{\lambda_{0eff}} = 2m\pi \quad m = 1, 2, \ldots \quad (3)$$

where l is the electrical length of the delay line, and λ_{0eff} is the effective wavelength in the delay line.

The phase delay at the LO carrier frequency f and the scanning angle from the broadside direction have a relationship:

$$\alpha(f) = \frac{f-f_0}{f_0}\frac{2\pi l}{\lambda_{0eff}} = -\pi\sin(\Delta\theta) \quad (4)$$

Thus, the scanning angle can be expressed as

$$\Delta\theta = \sin^{-1}\left[-\frac{f-f_0}{f_0}\frac{2l}{\lambda_{0eff}}\right] \quad (5)$$

In the proposed array, $l = 2\lambda_{0eff}$ is chosen so that the maximum scanning of ±20° is given at the selected minimum and maximum LO carrier frequencies ($f = f_{min}, f_{max}$) summarized in Figure 2.

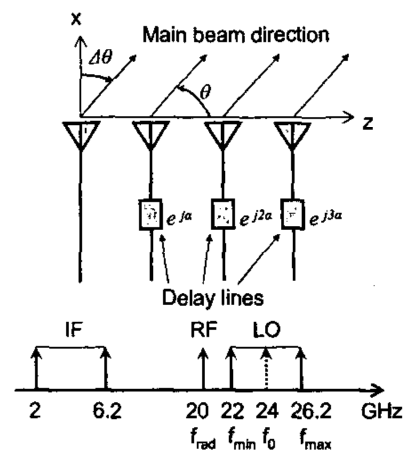

Fig.2 Operation diagram and frequency allocation of the array.

III. COMPONENT DESIGN

Since the system needs very accurate amplitude and phase distribution to promise reliable operation, very careful component designs are required. The arrays consist of four key components: power dividers, delay lines, wire-bonds, and mixers. In particular, special care must be taken for delay lines and wire-bonds to obtain less amplitude and phase errors between elements. To make a narrower frequency scanning range, longer delay lines are needed. However, longer delay lines result in undesired amplitude variations among the individual antenna elements. This effect can be neglected if the mixer is pumped sufficiently hard enough, since the RF output will become saturated when the LO is driven beyond a certain point. The trade off between the length of the delay line and frequency scanning range is thus important away from this operation point. Figure 3 shows the MOM simulation results of the insertion loss and phase of the delay lines. The delay line length between elements must be chosen so that an acceptable amplitude variation between elements with narrower frequency scanning range can be obtained in order to achieve less sidelobe levels and better radiation patterns in terms of beam steering at the same time. In this point of view, the delay lines are designed so that each neighboring element has 4π phase difference at the center frequency (f_0) of the variable LO carrier. Therefore, the phase delays of three delay lines in the 2nd through 4th elements installed in the LO line are respectively set at 2, 4, and 6λ in terms of effective wavelength at f_0=24 GHz compared to the straight line in the first element. As a result, the amplitude variation between the longest delay line (6λ delay length plus 3λ length at 24 GHz) and the straight line (3λ length at 24 GHz) is less than 1.5dB and its phase variation is restrained less than 1 degree at f_0=24 GHz.

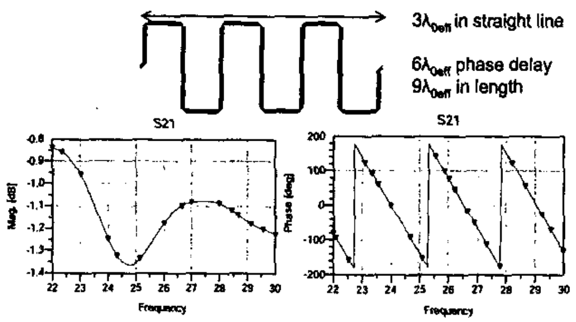

Fig. 3 MOM simulation results of the insertion loss and phase of the longest delay line (9λ in length, 6λ phase delay).

Another issue comes from the wire-bonds implemented in the IF line at the cross points to the LO lines. Figure 4 shows the MOM simulation model and the actual picture of wire-bonds installed in the IF line. Four gold wire-bonds with 1-mil diameter are used to connect a gap of a pair of the 9.7-mil wide 50 Ω microstrip lines in the IF line. Each gap between a pair of microstrip lines is 20 mils. Figure 5 shows the MOM simulation results of the insertion loss of wire-bonds. The insertion loss is less than 1.0 dB with the phase variation less than 5 degrees to cover a whole IF frequency range from 2 GHz through 6.2 GHz, in comparison with the equivalent length of straight microstrip line. Since lengths of wire bonds are identical (around 30 mils), the maximum phase variation between elements is less than 10 degree, which promises less than 3-degree scanning error. The isolation between LO and RF lines is better than 25 dB. Figure 6 shows a picture of one of the installed mixers in the array. Commercially-available passive double-balanced MMIC mixers (Hititte HMC 292) are used. The LO, IF and RF ports of the mixer in each element are connected using 1-mil diameter wire-bonds whose lengths are all less than 20-mils.

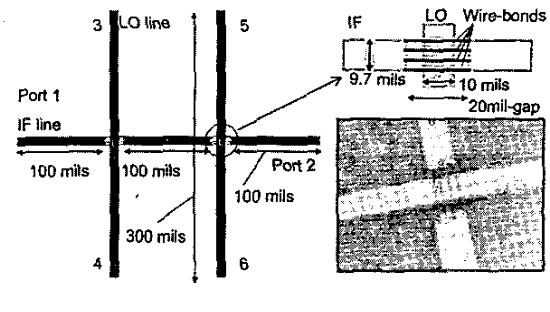

Fig. 4 MOM simulation model and a picture of wire-bonds installed in the IF line.

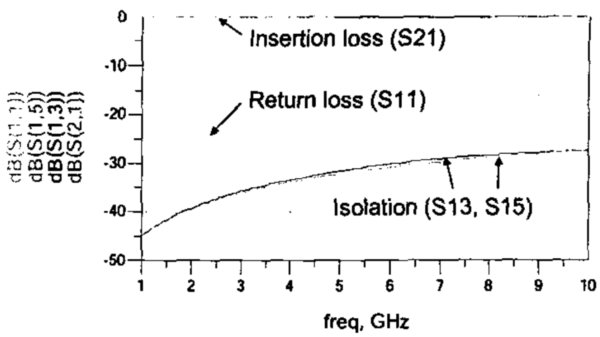

Fig. 5 MOM simulation result of the insertion loss of wire-bonds.

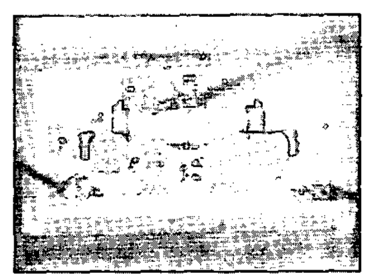

Fig. 6 Picture of the installed mixers.

IV. MEASUREMENT RESULTS

Figure 7 shows the overall return loss at the LO line input, including antenna elements, mixers, power dividers, delay lines, and wire-bonds. The LO and IF lines are constructed using 50 ohm microstrip lines with simple Wilkinson power dividers to have a necessary isolation between elements. The measured return loss for each line is better than -10 dB in each operation frequency.

Figure 8 shows the scanning characteristics of the K-band prototype array. The E co-polarization pattern in the radiation frequency (20 GHz) is measured in an anechoic chamber. The LO input power is set at +13 dBm for optimum pumping, while the IF input power is 0 dBm. The prototype shows the well-defined broadside pattern at 24 GHz in LO frequency and maximum scanning angles of -20.5 deg at 26.2 GHz and +19.5 deg at 22 GHz. The sidelobe levels are better than -12 dB even in maximum scan angles. In addition, these scan angles match the theoretical values in equation (5).

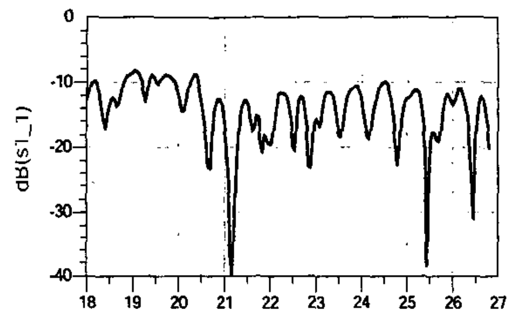

Fig. 7 Overall return loss of the LO line.

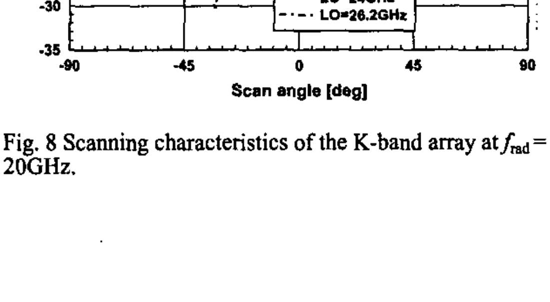

Fig. 8 Scanning characteristics of the K-band array at f_{rad} = 20GHz.

V. CONCLUSION

A novel compact K-band frequency-controlled beam steering array using mixing frequency compensation scheme is proposed. The use of the quasi-Yagi antenna element ensures broadband characteristics with well-defined radiation patterns in spite of its very compact size. The mixers are pumped with sufficiently large LO power to minimize amplitude imbalance at the RF output over a broad frequency range, leading to broadband operation. A prototype array antenna fabricated on the Alumina substrate achieves very compact size and one-side layout. The K-band prototype successfully demonstrates 40 degree scanning with a well-defined beam pattern by shifting the LO frequency from 22 GHz to 26 GHz, while a constant radiation frequency at 20 GHz is maintained by adjusting the IF frequency from 2 to 6 GHz. This single card antenna represents a low cost, low power, broadband phased array antenna without expensive phase shifters and can easily be expanded to larger 2-D arrays by simply stacking cards.

ACKNOWLEDGEMENT

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