Integrated Active Antenna Array Using Unidirectional Dielectric Radiators

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***Abstract*—In this paper, design considerations and experimental investigations of an integrated active antenna for space power combining that makes use of unidirectional dielectric radiators (UDRs) are presented and discussed. Attractive electrical performance stemmed from proprieties of nonradiating dielectric waveguide structures is benefited to design a prototype at a frequency of 14 GHz. An UDR feed circuit is implemented by microstrip lines and aperture-coupling is studied experimentally for arrays of two, four, and eight radiators. Measurements show high coupling and radiation efficiencies of the proposed excitation method. A power-combining efficiency of 89% was measured and a gain of 23.1 dBi was achieved for an antenna with eight radiators and four amplifiers. It is also shown that such a circuit configuration allows the combination of planar Ku-band monolithic hybrid microwave integrated circuit and UDR components in flexible design of active array antennas.**

I. Introduction

INTEGRATED active antenna elements and power-combining techniques have been developed in order to overcome the fundamental limitations on output power of semiconductor circuits at high frequencies, particularly in the millimeter-wave range and higher. Also, transmission lines suitable for integrated circuits become lossy at higher frequencies due to increased radiation loss and ohmic effect.

The active array is a highly suitable solution for the transmission of signals with distributed low-power solid-state sources. Although the power available from individual microwave semiconductor devices is much less than that from typical vacuum tubes, the power output from individual low-power sources associated singly with many array elements combines in space to form a high-power coherent beam, when the individual sources are synchronized in phase. The use of solid-state sources instead of vacuum tube brings many advantages. It makes possible an implementation of a relatively flat integrated assembly using miniature microwave-circuit techniques reducing the size and weight. The solid-state amplifiers use a low-power supply voltage, which eliminates problems associated with high-voltage breakdown. Another advantage of distributing the devices into an array is the lower RF losses between the output of the final amplifier and the radiating element due to the small distance between amplifier and radiator.

Quasi-optical power combining using either the active antenna or grid approaches has been an area of growing interest [1]–[9]. In most of these papers, the radiating elements are rectangular or

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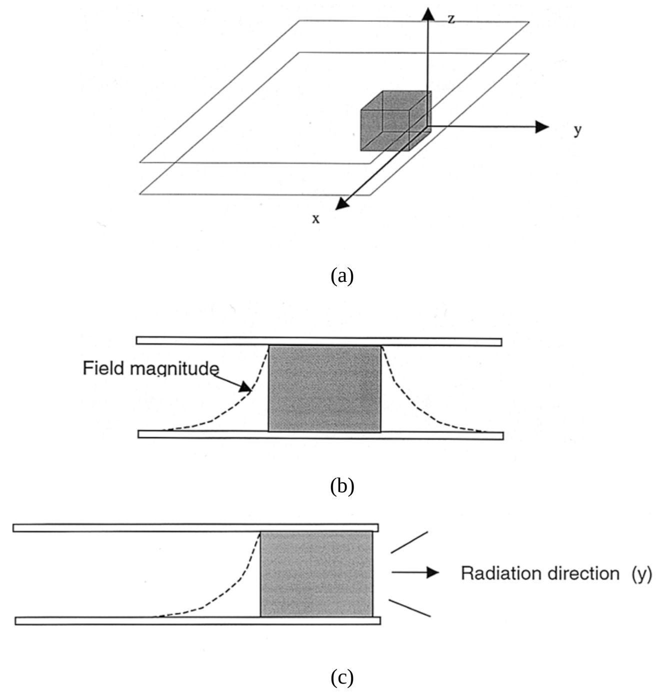

Fig. 1. (a) UDR. (b) Magnitude of the field in the air region. (c) Radiation condition.

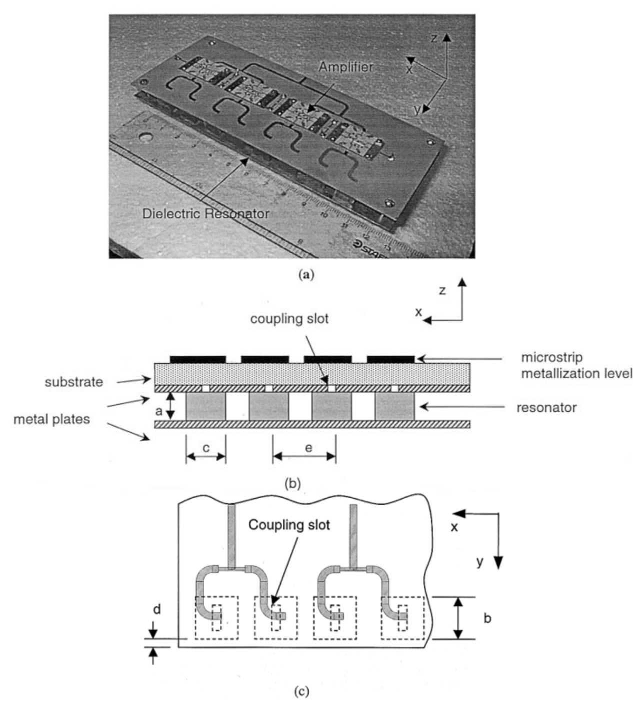

Fig. 2. UDRA structure. (a) UDRA with eight dielectric resonators and four amplifier cells. (b) Side view. (c) Top view.

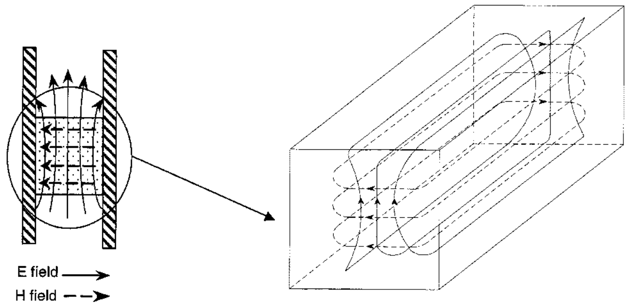

Fig. 3. LSM mode in the dielectric resonator.

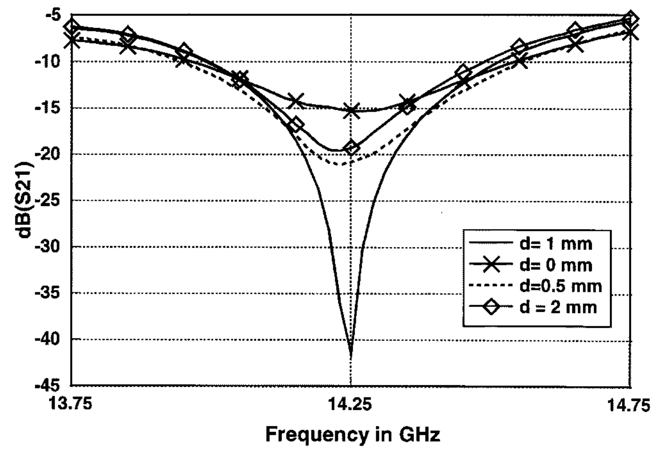

Fig. 4. Measured return loss S_{11} for different values of d.

circular patch antennas, which, at high frequencies such as Ku-, Ka-, and millimeter-wave bands may become very lossy. Another approach is the design of active integrated antennas in multilayer structures, which is a current trend for practical applications [10], [11]. In this case, passive radiating elements and active circuitry are designed and optimized on different substrates. The coupling between active circuitry and radiators is made through apertures in the ground plane separating these two substrates. The active circuitry can be fabricated on semiconductor substrate monolithically, and the antenna elements can be fabricated on another substrate with a lower dielectric constant for greater radiation efficiency [10]. This type of integration is compatible with monolithic-microwave integrated-circuit (MMIC) technology. In those papers, the antennas are implemented with patches. This paper features another approach based on dielectric-resonator antennas, which requires a more complicated modeling of the junction between the active microstrip circuits and radiators. On the other hand, such dielectric antennas have low-loss characteristics that may become an advantage as the frequency is increased to the millimeter-wave range.

The nonradiative dielectric waveguide (NRD) [12] has been demonstrated to be a highly attractive alternative in millimeter-wave circuits because of its simplicity, ease of fabrication, and low-loss nature. A promising dielectric antenna, namely, the unidirectional dielectric radiator (UDR) was proposed in [13]. As shown in Fig. 1(a), it is basically a short section of rectangular dielectric cylinder, which retains all the merit of NRD guide and, therefore, has great potential for millimeter-wave applications. To understand better its operating principle, consider a dielectric

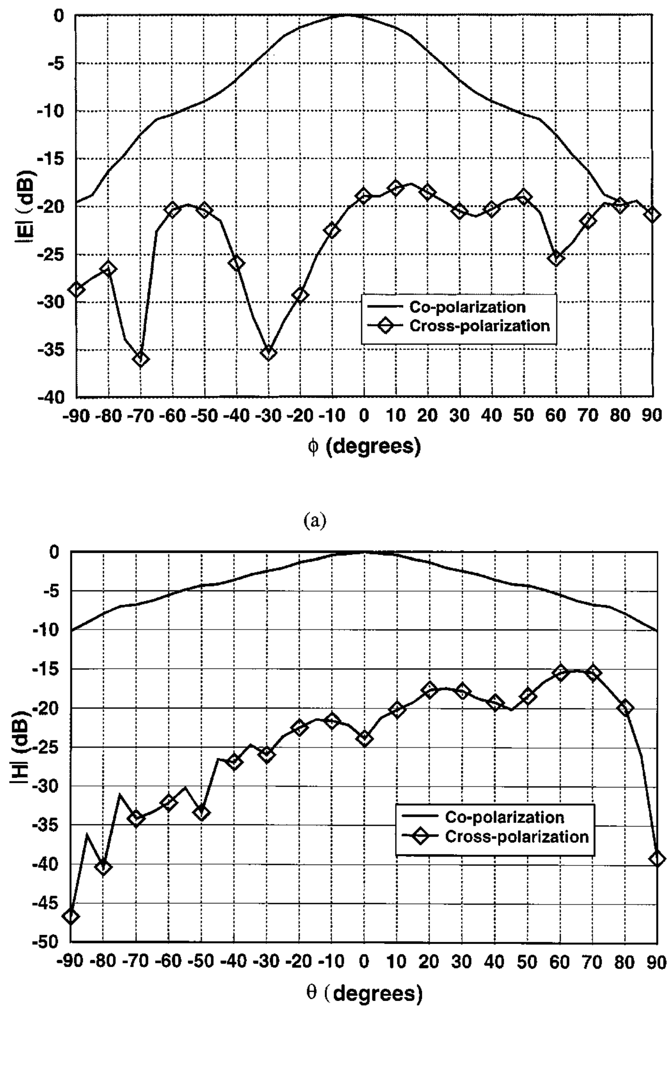

Fig. 5. Measured passive UDR antenna for one resonator. (a) E-plane. (b) H-plane.

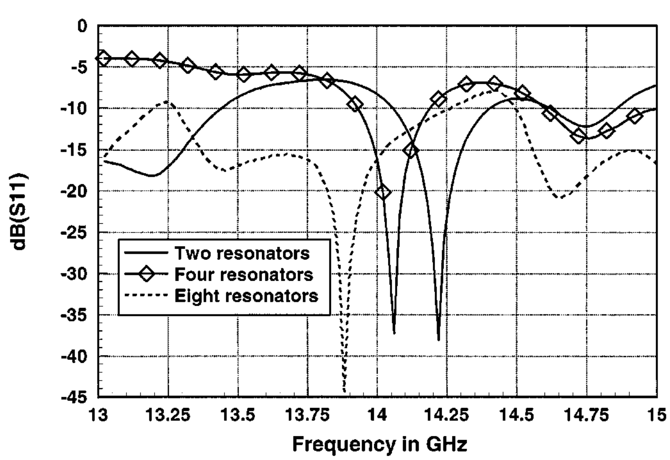

Fig. 6. Frequency response of the array for two, four, and eight elements.

cube inserted between two infinitely extended metal plates, which effectively forms a dielectric resonator. As is well known, if two parallel metal plates are separated by a distance smaller than

TABLE I
MEASUREMENTS OF THE DIFFERENT UDR ANTENNAS

	Resonant frequency GHz	Gain of the antenna dBi	Beamwidth		Sidelobe level
			E-plane	H-plane	
One resonator	14.25	7.12	60°	120°	no
One resonator with amplifier	14.25	16.9	60°	120°	no
Two resonators (e = λ/2)	14.1	9.3	50°	120°	no
Two resonators with amplifiers	14.1	18.1	50°	120°	no
Four resonators (e = 3λ/4)	13.94	11.45	21°	120°	-12.76 dB
Four resonators with amplifiers	13.94	20.0	21°	120°	-12.76 dB
Eight resonators (e = 3λ/4)	13.8	13.91	9.5°	120°	-13.22 dB
Eight resonators with amplifiers	13.8	23.1	9.5°	120°	-13.22 dB

one-half of the free-space wavelength, electromagnetic waves with the electric field parallel to the plates cannot propagate between them because of the cutoff properties. This structure then becomes an NRD resonator, which was used as a high-Q resonator element in NRD filter design. The mode of interest in the NRD is a longitudinal section magnetic (LSM) mode. This mode has its fields concentrated in the dielectric region at the working frequency and its fields, in the air region, are decaying away form the dielectric region, as illustrated in Fig. 1(b). If the metal plates have finite extent and the dielectric resonator is located in close proximity of the plates edges, as shown in Fig. 1(c), the complete nonradiative condition is no longer satisfied and the electromagnetic energy begins to radiate toward the open space, mostly in the y-direction. The NRD is then called an UDR. A cavity model for radiation analysis of the UDR was proposed in [14], which yields good agreement between calculations and measurements. Microstrip line excitation of an aperture-coupled UDR was proposed in [15]–[17]. In this paper, realizations showing the good performances of the UDR antenna and its potential use in the design of active UDR array antenna are presented. The design of the antenna begins with the study and experimentation of a simple UDR antenna made with only one dielectric resonator. This step is followed by the integration of an amplifier mounted on miniature microstrips to make a hybrid system that benefits the advantages of the two schemes (active planar circuits and UDR). The results have proven that the passive UDR antenna can be used to make a very good directive antenna with low RF losses. The comparison between radiation pattern of active and passive UDR antennas shows that the gain of the antenna was significantly improved with the addition of the amplifier with only minor disturbances on the radiation pattern. This step was then followed by the integration of active UDRs into two-, four-, and eight-element arrays.

II. RADIATING ELEMENTS

The structure of the aperture-coupled URD is show in Fig. 2. It consists of a number of identical dielectric resonators (dimensions $a \times b \times c$) located in close proximity (distance $= d$) to the edges of two large parallel metal plates. The resonators are separated by an equal distance e. The distance (a) between the two metal plates is smaller than the half-wavelength of the highest operating frequency. Therefore, all the guided modes between the plates are cutoff, except the TEM wave, which may appear as a parasite. However, it is possible to suppress this mode with vertical metal posts between the two plates without significantly affecting the antenna performance. The resonators are coupled to a feeding microstrip line through a small slot in the top plate, which also serves as one of the shielding planes of the UDR structure. The coupling longitudinal dimension of the slot is chosen to be perpendicular to the edge of the radiating aperture so as to excite the desired UDR LSM mode in the dielectric resonator (see Figs. 2(c) and 3). The energy leaks from the resonator into open space through the radiating aperture and it is suppressed in the other directions due to the cutoff properties of the metallic structure. According to the field distribution of the LSM mode, the antenna E-plane will be the xy-plane, and the H-plane will be plane yz.

III. PASSIVE AND ACTIVE ARRAY RESULTS

A. Passive Arrays

Prototypes of the proposed passive and active UDR antenna including one, two, four, and eight elements were built and tested. A corporative microstrip feed network using a Wilkinson

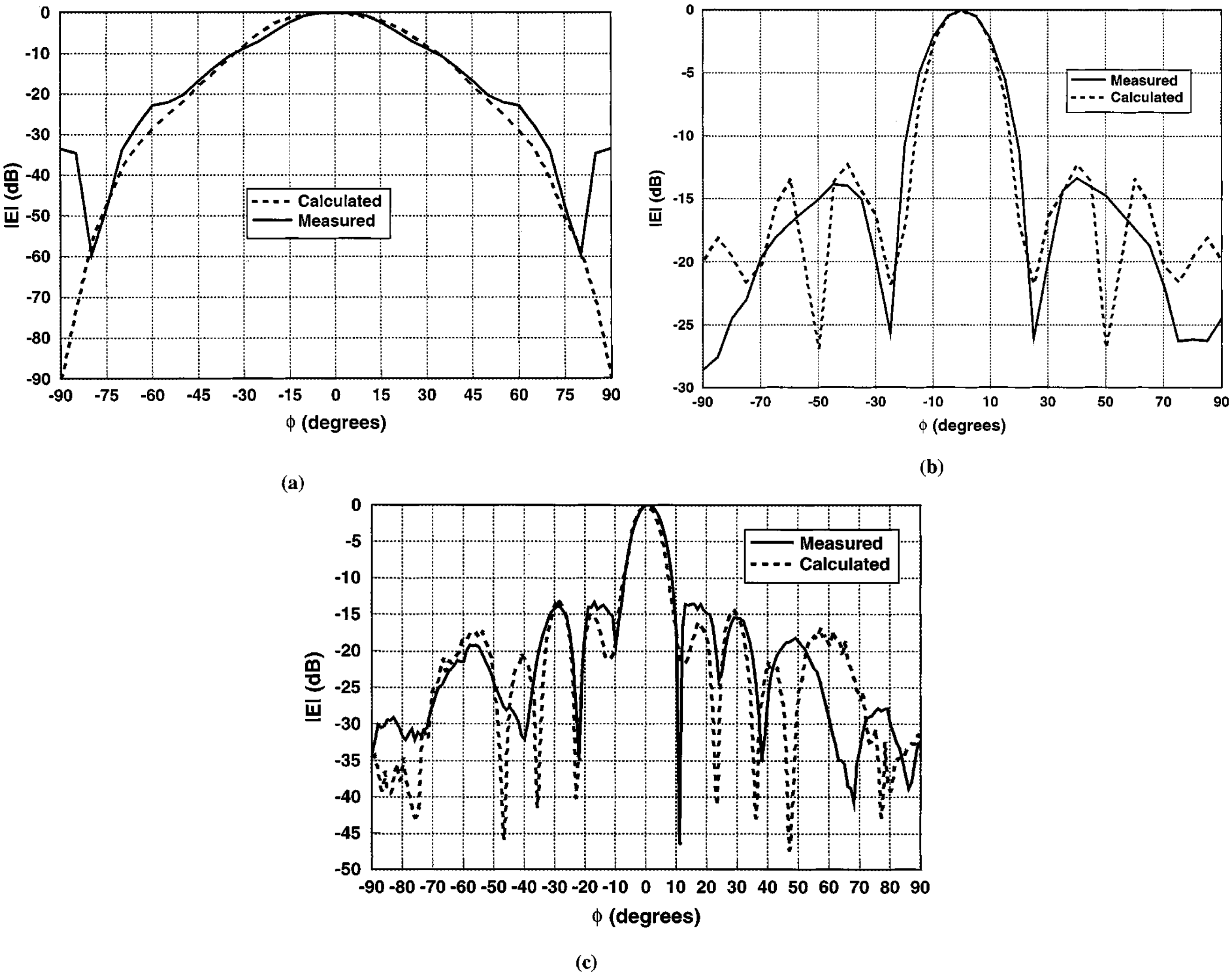

Fig. 7. Calculated and measured patterns of UDRA (E-plane). (a) Two elements. (b) Four elements. (c) Eight elements.

power divider and rectangular polystyrene ($\varepsilon_r = 2.55$) dielectric resonators were used. As a first step, a single resonator was designed to have a resonant frequency of 14.25 GHz for fundamental UDR LSM mode. The dimensions $a = b = c = 9$ mm were determined by the numerical method described in [14], which assumes that the resonator is trapped between infinite metal plates, which is without edge radiation. The measured return loss of the microstrip-fed single UDR with finite ground plates versus frequency is shown in Fig. 4. It can seen that the measured resonant frequency slightly varies as function of d. For $d = 0$ mm, 0.5 mm, 1 mm, and 2 mm, these frequencies are 14.24, 14.25, 14.25, and 14.26 GHz, respectively, which are very close to the predicted value of 14.25 GHz for an infinite d. High return-loss values are indicative that excellent coupling efficiency can be obtained. The radiation pattern measurements for a single-resonator antenna is illustrated in Fig. 5. The half-power beamwidth (120°) on the H-plane pattern is much larger than in the E-plane pattern (60°). The gain of the passive UDR is equal to 7.1 dBi. For UDR, due to mutual coupling between the resonators, the measured resonant frequencies differ significantly from that of the isolated resonator. Fig. 6 and Table I gives the frequency response of the arrays of two, four, and eight elements and the measured resonant frequencies, respectively, at the input of the feeding network. The decrease of the resonant frequency, with an increasing number of resonators, can be justified by considering mutual coupling. With only one resonator, the field distribution decays abruptly in the x-direction outside the dielectric. When other resonators are added in close proximity, there is a slight spread of the field distribution in the x-direction around a resonator, which is a similar effect than an increase of the resonator width (c), also leading to a lower resonance frequency. This field spreading effect is further increased by an in-phase excitation of adjacent resonator, whereas the antiphase excitation confines the fields and, thus, increases the resonance frequency. Note that changing the mutual coupling and tuning of the resonant frequency can be achieved by adjusting the distance e between the dielectric resonators, but it will affect on the pattern of the array antenna.

A very important and special case for spatial power combining is that of an equally spaced linear and uniformly excited array. It is easy to calculate the pattern of the unidirectional dielectric-resonator arrays (UDRAs) for two, four, and eight elements. Taking the measured values plotted in Fig. 5 for the el-

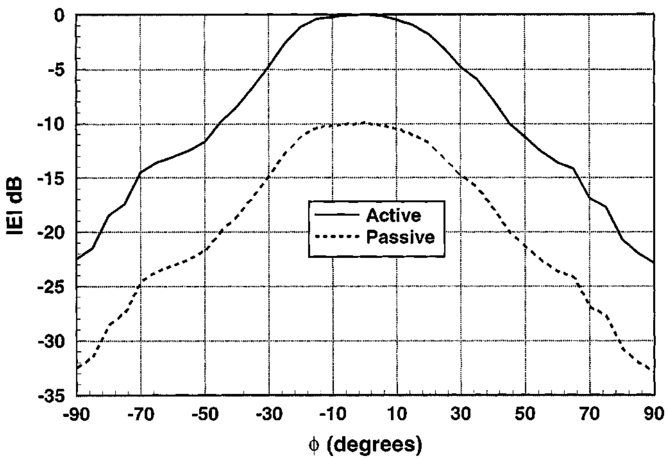

Fig. 8. Measured active passive UDR patterns for one resonator in the E-plane.

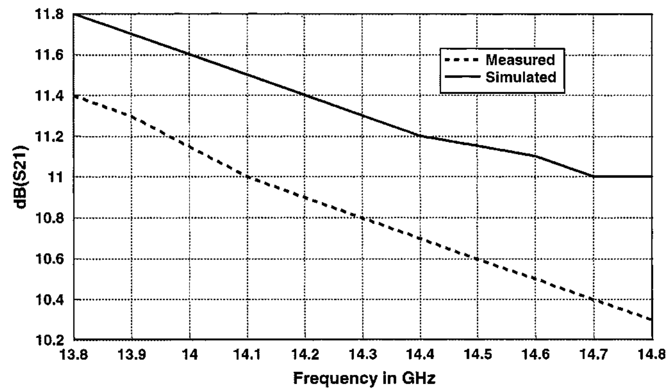

Fig. 9. Measured and simulated amplifier gain.

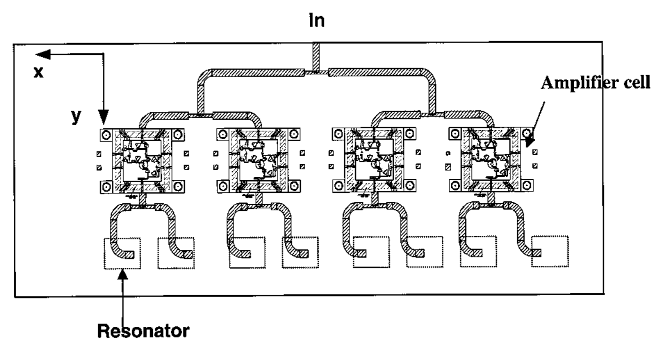

Fig. 10. Feeding network for active eight-element transmitting UDRA (top plane).

ement factor together with the theoretical array factor, we have calculated the expected patterns of the realized UDRAs. These patterns are compared to the measured ones in Fig. 7 for three UDRA prototypes. For the three cases, the measured and calculated main beams are in very good agreement. There are some differences in the sidelobes, which might be due to diffraction on the finite metal plate edges or to a nonuniform excitation profile of the resonators attributable to mutual couplings and slight path length differences in the feed network.

In the first case (two resonators), the distance between the resonators is $e = \lambda/2$. For the two other cases, this distance was increased to $3\lambda/4$ to compensate for some of the resonant frequency offset depicted in Fig. 6. This is done to keep the resonant frequency in the Ku-band and as much as possible near the center of the amplifying cell band of operation.

B. Active Array

The gain of the active antenna is divided into two parts: the gain of the amplifier (G_T) and the gain of the passive antenna (G_r). Thus, assuming matched conditions, we have

$$(G_a)_{\mathrm{dB}} = (G_T)_{\mathrm{dB}} + (G_r)_{\mathrm{dB}} \tag{1}$$

Gains of the passive and active UDR (for one resonator) are equal to 7.1 and 16.9 dBi, respectively. Fig. 8 compares the E-plane patterns of one-resonator active and passive prototypes. It can be seen that the integration of the amplifier with the UDR antenna does not disturb the shape of the radiation pattern of the UDR antenna significantly. Fig. 9 shows G_T versus frequency obtained by measurement and simulation with HP-MDS. According to this figure, a gain increase of 10.8 dB was expected for the active element, whereas an increase of 9.8 dB was achieved. The 1-dB loss may be attributed to a nonnegligible mismatch between the amplifying cell output and the slot-coupled resonator input. Fig. 10 shows the feeding network for the active UDRA. This feeding network allows us to excite the resonators with uniform amplitude and phase. The input signal is divided in eight using Wilkinson power dividers. Only one amplifier was used for each pair of output. Fig. 11 displays the measured E-plane pattern of four and eight resonators for active and passive configurations.

The measured gain of the four- and eight-element units are 20 and 23.1 dBi, respectively. Except for a constant gain offset, there are small differences between the active and passive patterns. These differences might come from the variation between the amplifiers, both in gain and phase. Another reason is that the active and passive antennas, due to the large number of resonators, have some mechanical differences.

For the eight-element antenna, the measured effective radio power (ERP) is 20.4 W and the dc input power to the UDR antenna is 360 mW. The power actually radiated from the antenna was calculated to be 100 mW, which gives a dc-to-RF conversion efficiency of 27.8%. Also, the power generated per device is 25 mW. This approximates the power expected from these devices (28 mW) biased at 3 V with a drain current of 30 mA. The combining efficiency is then 89%.

All measurements are relative with respect to a maximum level of 0 dB. They were all made under far-field conditions. Measurements were taken in the anechoic chamber and by using a horn antenna as a reference antenna. Measurements were made by using an automated measurement system. Finally, Table I summarizes all the measurement results of the active and passive UDRAs.

IV. Conclusion

Experimental and analytical results of active slot-coupled microstrip line-fed URD arrays have been presented in this paper.

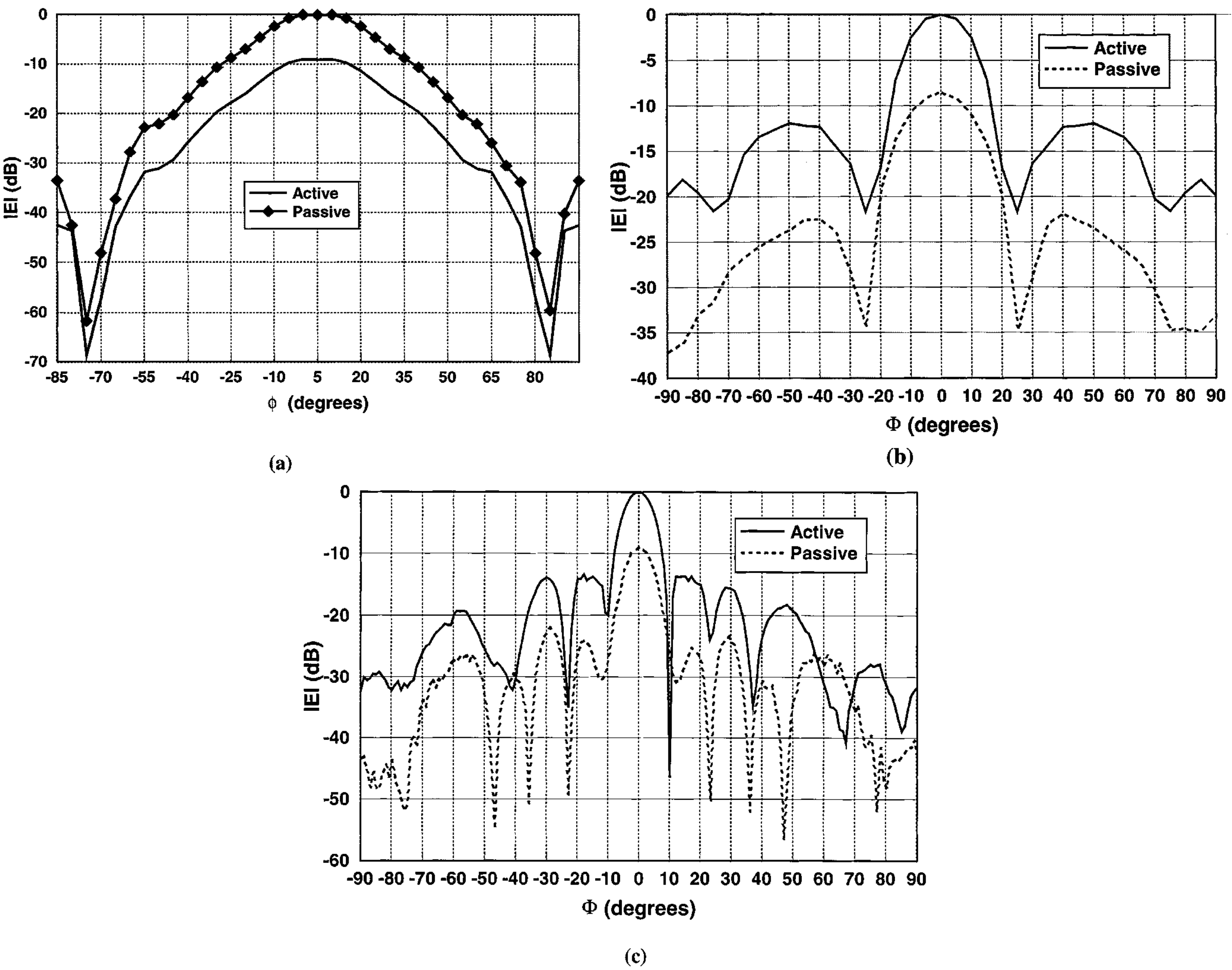

Fig. 11. Measured E-plane patterns using active feeding network. (a) Four resonators. (b) Eight resonators.

It is shown that combining UDR technology and planar circuits monolithic hybrid microwave integrated circuit (M(H)MIC) is possible, leading to good results, while advantages of each technology can be effectively combined.

It was experimentally found that coupling between adjacent resonators caused a nonnegligible negative shift of the antenna's resonance frequency. This effect can be somewhat compensated by increasing the distance between the array elements, but at the expense of an increase in the sidelobe level.

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