Quasi-Optical Transmit/Receive Front Ends

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(Invited Paper)

Abstract— **Quasi-optical (QO) active circuits have originally received interest for power generation by large-scale power combining of solid-state devices at microwave and millimeter-wave frequencies. Here, we present an overview of QO components developed with functionality in mind, with an emphasis on bidirectional amplifier arrays for transmit/receive (T/R) front ends. We discuss possible advantages of the QO architecture for communications and radar. The following three QO bidirectional arrays are presented: 1) a nine-element X-band patch antenna array with different polarizations in T/R modes; 2) a 24-element X-band slot lens array with switches for the T/R paths; and 3) a 22-element Ka-band patch lens array using monolithic microwave integrated circuits (MMIC's).**

Index Terms—**Active antennas, communications, quasi-optical, radar.**

I. INTRODUCTION

RADAR AND different kinds of communication systems at microwave and millimeter-wave frequencies for both military and commercial applications require transmit/receive (T/R) modules. Here, we discuss a new architecture for T/R analog front ends, in which an active element is integrated within each element of a (possibly) large antenna array. In transceivers, there is often not enough space to use two separate antennas for transmitting and receiving. A T/R analog front end with a single antenna needs to provide enough power in transmission, low noise in reception, and some way to isolate the transmit from the receive part. The quasi-optical (QO) approach has the potential to provide this, with some benefits compared to traditional architectures.

A conceptual sketch of a QO T/R analog front end is shown in Fig. 1. In transmission, the advantage of this architecture is that the radiated power from the array is obtained by combining the individual amplifier output powers [1]–[4]. Instead of a corporate feed with associated losses and dispersion, all elements are fed in phase from free space. This allows for lower cost and lower power individual elements and graceful degradation. In reception, the noise figure of the entire array is the same as that of the single element [5], while the received powers combine coherently. This increases the dynamic range of the receiver and improves its reliability.

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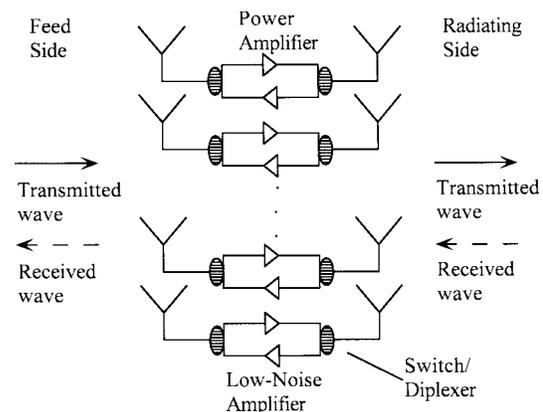
Fig. 1. A sketch of a general QO T/R analog front end.

In a transceiver, the T and R paths are separated in time, in which case, switches or circulators are used, or by using different frequencies and/or polarizations for transmission and reception, and employing diplexers. In the QO T/R components presented here, solid-state switches route the signals through the low-noise amplifier path or the power amplifier (PA) part in each unit cell of the array, or two polarization modes of a single patch antenna are used for T/R.

Elements of a QO transceiver that have been demonstrated over the past decade are reviewed in [6] and other papers in this TRANSACTIONS. Most of them focus on large-scale power combining with the goal of obtaining watt-level output powers at millimeter-wave frequencies and tens of watts at microwave frequencies. A few researchers have demonstrated power-combining arrays that include some functionality. For example, a grid oscillator was characterized as a self-oscillating harmonic and subharmonic mixer, and several such identical mixers were used in a diversity receiver where the front end was a QO lens amplifier array [7]. Furthermore, two different phase-shifterless beam-steering schemes have been demonstrated: an oscillator linear steering array using voltage-controlled oscillators (VCO's) to detune end elements of a self-injection locked array to produce a progressive phase shift across it in one dimension [8]; and using antenna arrays with integrated lensing, similar to Rotman lenses [9]. The former is reviewed in detail in [6], and the latter approach and its implications to T/R functions are overviewed here. In [9], a transmitting lens amplifier demonstrated beam steering and beam forming without mechanical motion or phase shifters integrated in the array elements. This is achieved by placing several transmitters along the focal surface of a lens. By
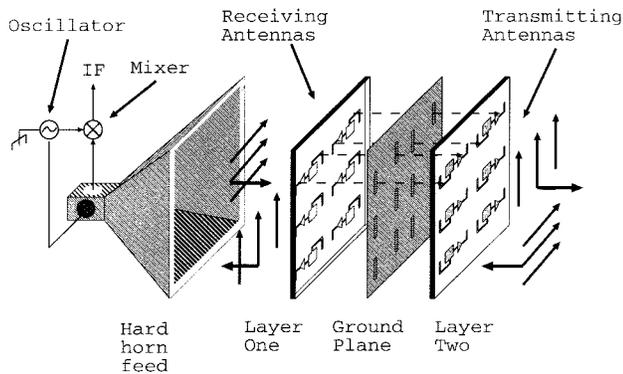
Fig. 2. Perspective view of a T/R double-layer X-band array.

turning the transmitters on and off, one can discretely steer the beam. Alternatively, several feeds can be turned on at the same time, allowing for forming nulls or sidelobes in desired directions. Some of the applications of this technique in T/R arrays will also be presented here.

In this paper, an overview of the following T/R arrays that have been demonstrated to date is presented:

1) X-band patch-antenna amplifier array that uses orthogonal polarizations for receive and transmit [10];
2) X-band slot-antenna lens amplifier that uses the same polarizations for receiving and transmitting [11];
3) hybrid Ka-band lens array with monolithic-microwave integrated-circuit (MMIC) PA's, low-noise amplifiers (LNA's) and switches, and a folded focus [12].

Some work on transceivers has been done in conjunction with retrodirective arrays [13], and is presented in detail in a different paper in this TRANSACTIONS; therefore, we have excluded retrodirective arrays from our discussion. There have also been demonstrations of single active transceiver antennas, e.g., [14] and [15], which could be used as elements of an array.

II. BIDIRECTIONAL AMPLIFIER ARRAYS

A. A Bidirectional X-Band Array Using Dual-Polarized Patch Antennas

The T/R double-layer spatial amplifier discussed next is based on previous work with double-layer amplifier arrays [2]. The sketch of a T/R QO array of this kind is shown in Fig. 2. In this case, the isolation between the two orthogonal edges of a microstrip patch antenna is used to provide the necessary isolation between the T/R ports for simplex operation, and the same antenna is used for T and R to save space.

The horizontally polarized input signal incident upon the surface of the spatial amplifier using a hard horn feed is received by an array of patch antennas and amplified. It is then coupled to the second layer where it is retransmitted into free space by the second-layer patch-antenna array having vertical polarization. The horizontally polarized incoming signal is received by the same patch antennas on the second layer. It is amplified and then coupled to the first layer, where it is radiated with a vertical polarization into the hard horn feed [16]. Isolation provided by the orthogonal edges of
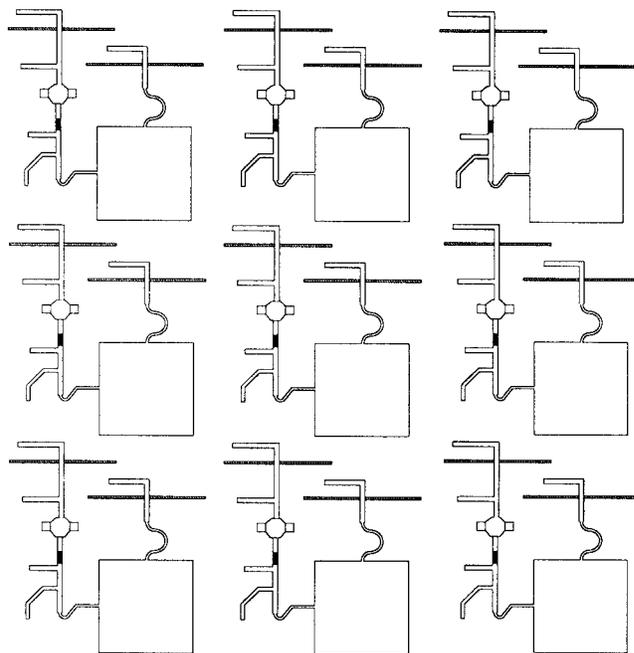

Fig. 3. Circuit layout of the 3×3 X-band T/R array. Transmitting and receiving sides have symmetrical layouts.

patch antennas (25 dB) isolates the receiving and transmitting amplifiers. Therefore, T/R switches are not required for this purpose. An orthomode transducer placed at the input to the hard horn allows for well-defined T/R ports. The 25 dB of isolation provided by orthogonal ports of patch antennas is not enough to prevent the receiver from being saturated while the transmitter is on, and during reception, the transmitter should be switched off. This method is commonly used in millimeter-wave T/R modules currently in production. One can envision the use of rectangular patch antennas instead of square patch antennas for transmission and reception at two different frequencies. Systems requiring duplex millimeter-wave communication may achieve enough isolation by using a diplexer for simultaneous operation of the transmitter and receiver. The isolation provided by using the orthogonal edges of the patch antennas relaxes the requirements on the design of diplexers.

Fig. 3 shows the circuit layout for a 3×3 T/R spatial amplifier array designed to operate at 10 GHz. In this design, either side of the double-layer amplifier array can transmit or receive, but for simplicity, one of the layers is referred to as the transmitting layer, and the other as the receiving layer. Details of the circuit and antenna design are given in [10]. The T/R array consists of nine unit cells and uses general-purpose high electron-mobility transistor (HEMT) devices (Fujitsu FHX06LG) for both T/R modes of operation. Resistors are added along the gate bias lines to prevent low-frequency oscillations.

The measurements were performed in a far-field setup, and the T/R gain measurements are shown in Fig. 4. In the measurements, first a through calibration between two horns in the far field was performed with the horns copolarized. The amplifier array was then inserted, and the through power measured with cross-polarized horns, since the array rotates
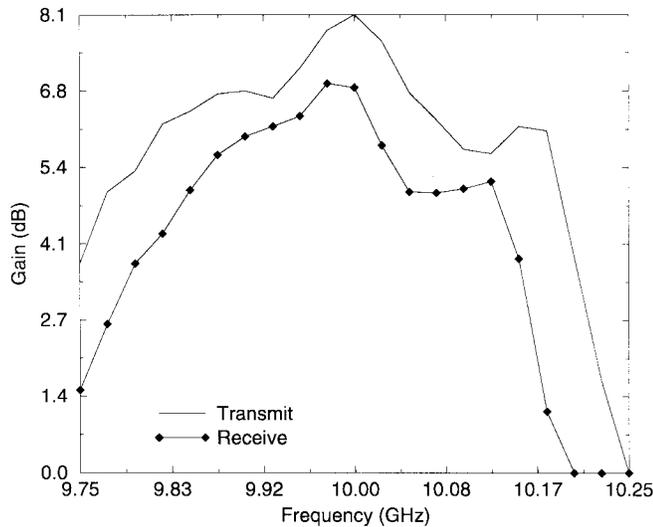
Fig. 4. T/R far-field gain measurements of the 3 × 3 T/R array.

polarization. The gains of the amplifiers are backed out through the Friis formula. Maximum gains of 8.2 and 6.8 dB were measured for T and R modes, respectively, centered at the design frequency of 10 GHz. The dissimilarity between the measured gains can be attributed to device parameter variation and fabrication errors. The 3-dB bandwidths for T and R modes are 400 and 350 MHz, respectively. ON/OFF ratios, measurements taken with the amplifiers biased and unbiased, were also measured to quantify the isolation between T/R layers, and were for both sides greater than 25 dB. Fig. 5 shows the measured radiation patterns at the design frequency of 10 GHz. The amplifier array has a measured beamwidth of about 60° in both planes, which is consistent with simulated results.

B. An X-Band Bidirectional Lens Amplifier Array Using Slot Antennas

The previously described array was designed to be fed from the far field, or possibly with external lenses or hard horn feeds. Below, we describe an array that is designed to be fed from one or more points along a focal surface in the near field of the array (focal distance to diameter ratio $F/D = 1.5$). The array is basically a two-dimensional planar amplifying Roman lens [17]. Each element of the input antenna array is routed through an amplifier and appropriate delay lines to the output antenna element. The delay lines and element relative positions define the focal points of the lens [9], [18].

Orthogonally polarized microstrip-fed antiresonant slot antennas were chosen as the radiating elements at the input and output because of their wide bandwidth (40%, $\mathrm{VSWR} = 2$). Each pair of slots is connected with a pseudomorphic HEMT (pHEMT) LNA in one path and a MESFET PA in the other. Two single-pole double-throw (SPDT) switches (each consisting of two p-i-n diodes) are used to switch between T and R paths. The dc bias for the diodes is supplied through the slot antenna feed lines. Both the PA and the LNA transistors share the same drain bias to reduce the number of bias lines.
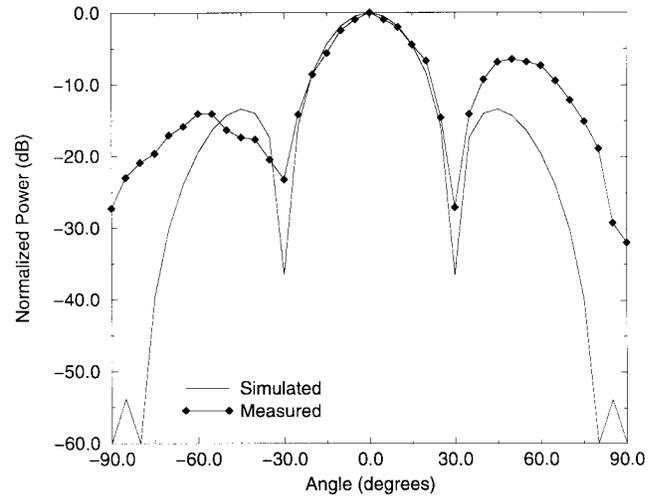

(a)
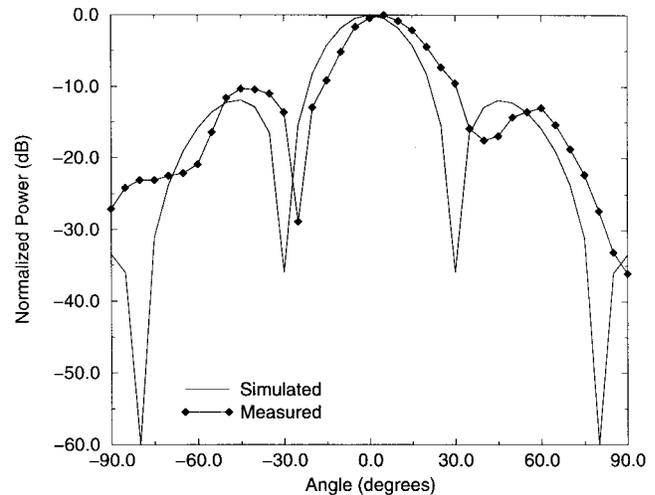
(b)

Fig. 5. Theoretical (solid line) and measured (symbols) radiation patterns in the (a) E-plane and (b) H-plane of the 3 × 3 T/R patch array at 10 GHz.

Details of the antenna and amplifier circuits are presented in [11].

First, a unit cell, shown in Fig. 6(a), was designed and characterized as a benchmark for the array. From a free-space measurement of a single unit cell, the gains contributed by the amplifiers are approximately calculated from the Friis formula, with a 5.5-dB gain used for the slot antennas with polarizers. The transmit amplifier has a maximum measured gain of 10 dB at 11 GHz. The receive amplifier has a measured gain of 7.5 dB at 10.8 GHz. Measured ON/OFF isolation of about 10 and 20 dB is seen for the receive and transmit amplifiers, respectively.

The bidirectional lens amplifier array consists of 24 elements in a triangular lattice with four elements in the first and fifth row, five elements in the second and fourth row, and six elements in the third row, as shown in Fig. 6(b). Lensing delay lines are incorporated between the antenna pairs in each unit cell. The delay-line lengths were calculated using the design equations for a lens with one degree of freedom [18]. The focal distance of the array is 27.5 cm.
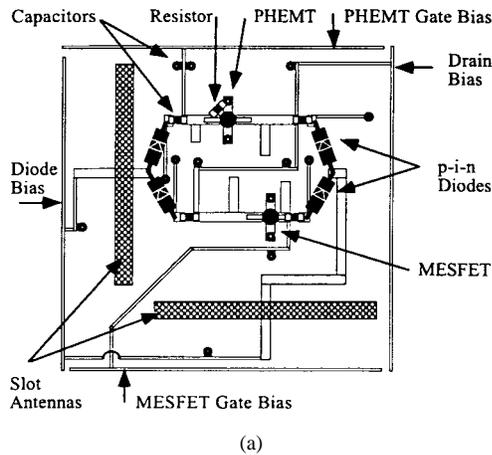
(a)
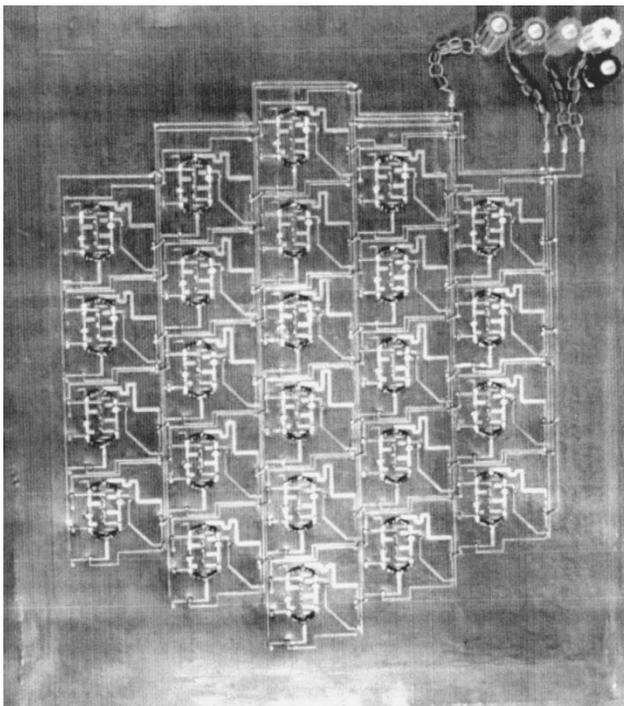
(b)

Fig. 6. (a) Unit cell of a slot-antenna T/R lens array. The slots are connected through transmit or receive paths by switching the p-i-n diodes. (b) Photograph of the circuit side of the 24-element bidirectional amplifier array. Orthogonally polarized slot antennas are located in the ground plane.

The measurements were performed as illustrated in Fig. 7. In transmission, an incoming plane wave from a vertically polarized horn is amplified by the transmit amplifier, reradiated as a horizontally polarized plane wave, and received by a horizontally polarized horn. In reception, an incoming plane wave from the horizontally polarized horn is amplified by the receive amplifier, reradiated as a vertically polarized plane wave, and received by the vertically polarized horn. Polarizers are inserted at a half-wavelength on each side of the unit cell to improve the gain. An identical passive array, with the amplifiers replaced by through lines between the two slots, is used for calibration with the T and R horns copolarized, and placed in an aperture cut out of absorbing material.

Note that the gain obtained in this way is not the same as the gain quoted for the far-field-fed array from Section II-A. The
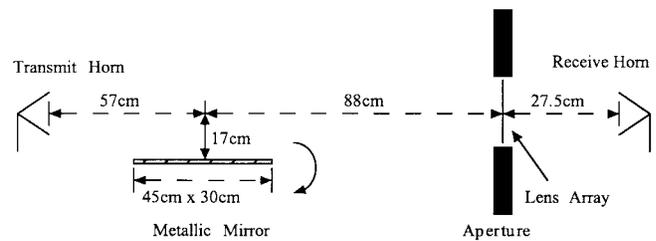

Fig. 7. Setup for measuring a lens amplifier bidirectional array. The translatable mirror is used only for a multipath reduction experiment, which is described in Section III.

gains for the patch array were backed from the Friis formula and are amplifier gains. The gains measured for the lens are "system" gains and represent the increase in received power when the lens is inserted into the free-space path.

Measurements were first performed with the ten central elements populated. A measured ON/OFF isolation of 25 dB for both receive and transmit modes with ten elements is seen. In the receive mode, a maximum power gain of about 10 dB relative to the passive array with ten elements is measured at 9.4 GHz. In the transmit mode, the measured power gain is about 5 dB at 10.2 GHz.

These measurements were repeated with all 24 elements populated; the results are plotted in Fig. 8. In the receive mode, a maximum power gain of 5.5 dB relative to the passive array with all 24 elements connected is measured at 10.1 GHz. In the transmit mode, the measured power gain is 2.0 dB at 10.2 GHz. (A possible explanation for reduction in gain when increasing the size of the array from 10 to 24 elements is increased nonuniformity of the amplifiers across the array. This could be due to fabrication, unmatched devices, coupling between unit cells, as well as a larger fraction of edge elements in the 24-element array, as compared to the ten-element array.) The absolute power gain relative to the rectangular aperture is 3.9 dB in reception and 0.9 dB in transmission. The physical area of the active antenna array only covers 55% of the aperture, so the absolute power gains are expected to be higher than those measured. Measured ON/OFF isolation ratios of about 15 dB in the receive mode, and more than 20 dB in the transmit mode are seen. The 24-element lens amplifier has a measured beamwidth of about 10° in both E- and H-planes, with sidelobe levels of less than −10 dB, as shown in Fig. 9. The theoretical patterns were calculated for a uniform array using the measured radiation pattern of a single-slot antenna and assuming no coupling between unit cells.

C. Ka-Band Lens Array Using Commercial MMIC's

A similar lens array as the one in Section II-B was designed for Ka-band [12]. Patch antennas with ground-plane slot couplers are used. The patches give good input/output isolation, and the slot couplers are broad-band (5 GHz at 30 GHz) and easy to fabricate. The array is constructed on two Roger's TMM10 substrates. The ground planes are soldered together, and one of the substrates has holes in which MMIC PA, LNA, and SPDT switch chips are bonded. The front and back sides of the array, as well as the unit cell front and back sides, are shown in Fig. 10. This lens uses a folded focus, thereby
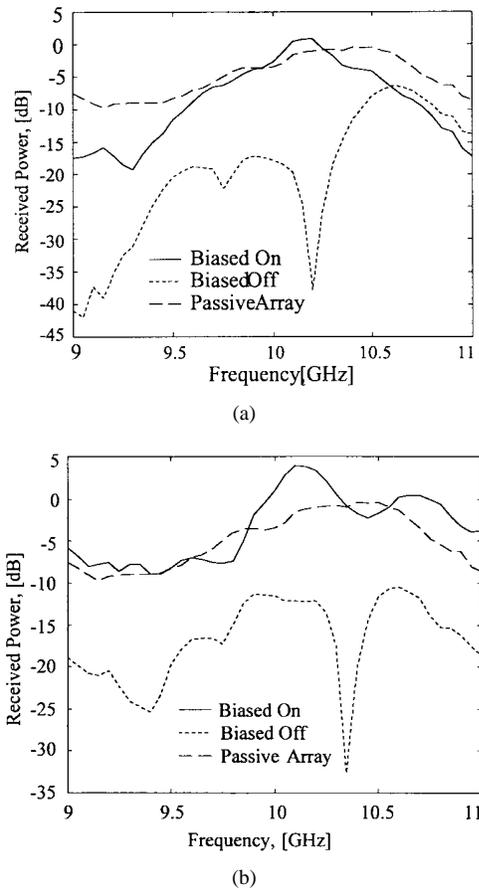
Fig. 8. (a) Measured ON/OFF ratio of the 24-element active and passive array in transmit mode, with polarizers at input and output. (b) Measured ON/OFF ratio of the 24-element active and passive array in receive mode, with polarizers at input and output. The measurements are normalized to a through measurement with a rectangular aperture surrounded by absorbing material. The solid lines represents the biased on state, the dotted lines the biased off state, and the dashed lines shows the measured results for the passive array.

Fig. 9. (a) Measured (–) and simulated (– –) E-plane radiation pattern for the receive amplifier at 10.1 GHz. (b) Measured (–) and simulated (– –) H-plane radiation pattern for the receive amplifier at 10.1 GHz. The theoretical patterns were calculated for a uniform array using the measured antenna pattern of a single-slot antenna.

decreasing by a factor of two the overall size of the array along the optical axis, as sketched in Fig. 11. The middle element of the active lens is left as a feed element. A passive lens was first fabricated and used to estimate a 2.7-dB loss due to just the passive parts of the array. A single active unit cell was fabricated and demonstrated 15- and 12-dB gains in the T and R directions, respectively. The array is thermally stable with no cooling, but the gain is 3 dB higher if the amplifiers are air cooled. The array was populated in subarrays, and Fig. 12(a) shows the measured gain in transmission as the number of elements increases. For 17 elements, the measured absolute power gain as compared to a free-space path between two copolarized horn antennas is 7 dB in Ka-band. Fig. 12(b) shows the measured temperature profile across the array with and without convection air cooling using a simple fan. The temperature was measured by moving a thermocouple across the MMIC side of the array. The array is currently being further populated, and more detailed results will be reported shortly.

All three arrays described above show the feasibility of QO T/R front ends and scaling from X- to Ka-band hybrid arrays. At higher millimeter-wave frequencies, monolithic integration might be more attractive.
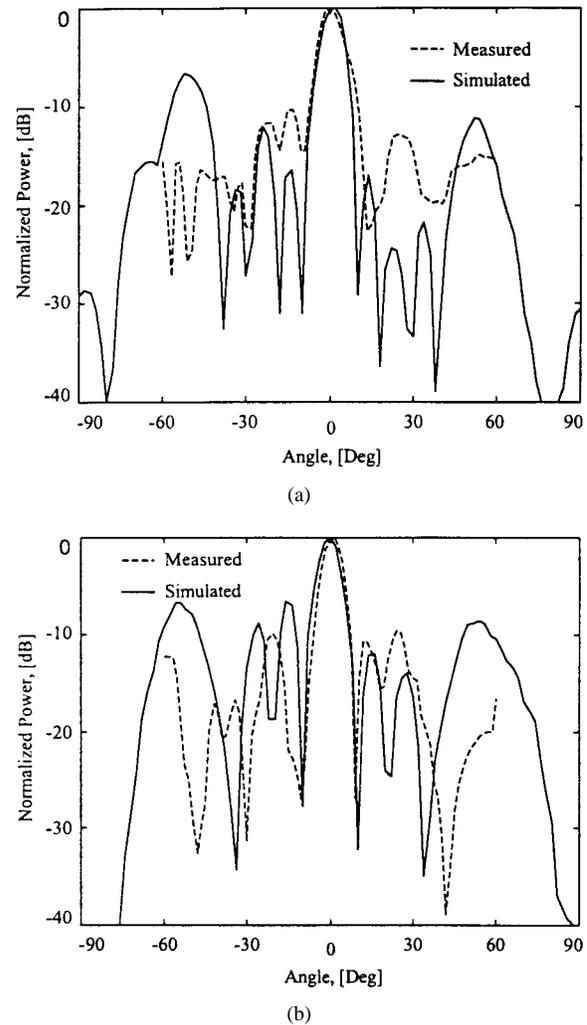
III. FUNCTIONALITY OF QO T/R ARCHITECTURE IN COMMUNICATION AND RADAR SYSTEMS

Do QO T/R amplifiers and front ends offer any added functionality compared to other approaches? Some interesting possible advantages have been demonstrated with communications and radar in mind, and are described below. An important impact of QO components is that they simplify the modular design of T/R front ends. A simple communications example is presented in [11], where a lens amplifier is cascaded with a grid self-oscillating mixer, and a 10-kHz amplitude modulated X-band carrier is demodulated from a 290-MHz intermediate frequency (IF) taken directly from the grid bias lines.

A. Distributed Transmitters for Communications

In communications, often a single antenna is used for T/R. In mobile systems, such as a cellular and personal communication system (PCS), this is the case both at the mobile unit and base station. The arrays described above would be appropriate for base-station antennas. On the transmit end,
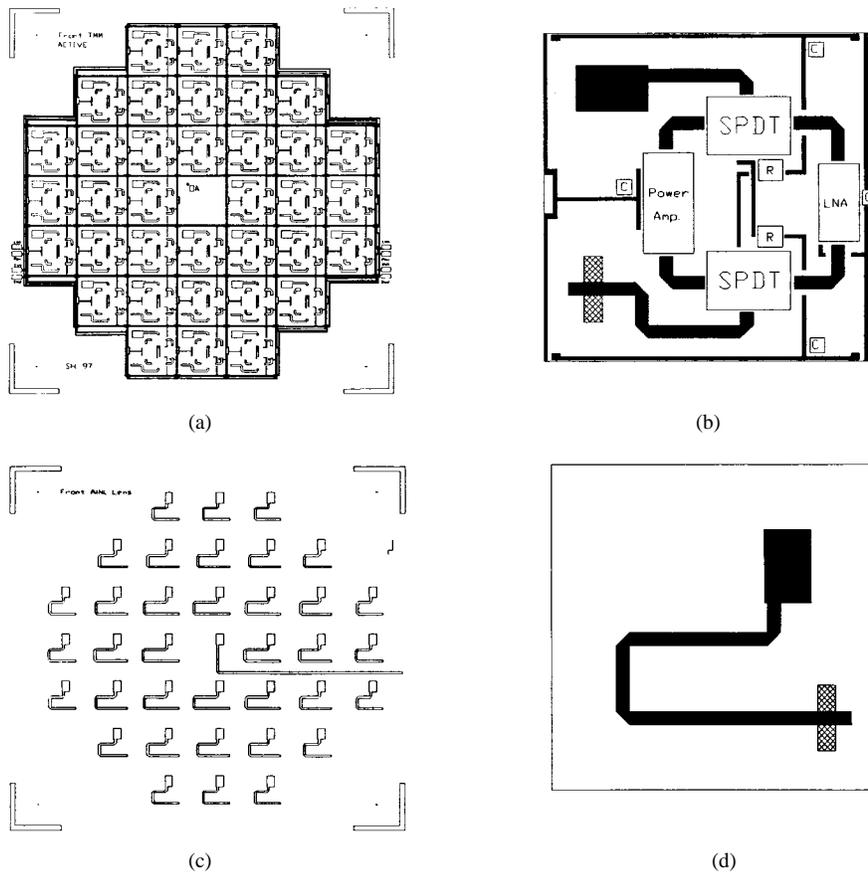
(a)

(b)

(c)

(d)

Fig. 10. (a)–(b) Front and (c)–(d) back sides of a patch-antenna hybrid Ka-band bidirectional lens amplifier array and unit cell. The unit-cell size is $1\lambda^2$.

usually on the order of 100 W is required [19] with more than 10 dB of gain (depending on the number of sectors), which would mean that in the QO implementations, each PA would need to have on the order of a watt of output power, readily available today with reasonable efficiencies up to millimeter-wave frequencies. This would also be advantageous for local microwave distribution system (LMDS) head-end master transmitters or for the repeaters, which require on the order of 60 W in the 27–30-GHz range. These systems currently use traveling-wave tubes with either omni-directional antennas or horns with various gains, and with orthogonal polarization with a cross-polarization isolation ratio of at least 20 dB, and typical weights between 700–2500 N. QO technology would improve the reliability of these systems, as well as decrease the size and weight.

B. QO Architecture for Multipath Fading Reduction and Diversity Reception

One of the problems in communications is the fact that antennas have a "dead spot" in certain directions because of the nulls in the radiation pattern. Nulls are also encountered in a multipath fading communications propagation channel when the direct path signal destructively interferes with a signal that is reflected off of some obstacle before arriving to the receiver [20].

These problems can be eliminated with a lens amplifier by placing multiple receivers at the focal surface. This has been demonstrated at X-band with simple self-oscillating receivers
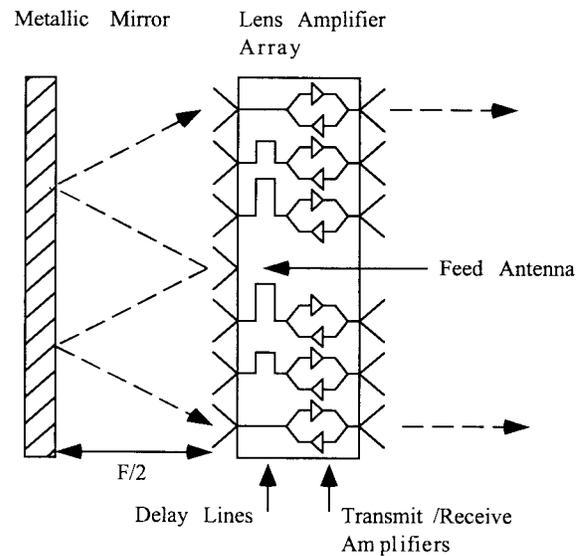

Fig. 11. "Folded" lens amplifier geometry. The lens is fed by its center elements, which does not contribute directly to the combined output power.

[7]. Fig. 13 shows the three measured received IF signals (which can be summed up after IF filtering) as the source is moved in the far field in the E-plane. It has been shown that this architecture also reduces the effects of multipath fading since the lens has built-in angle diversity. For example, if three receivers are placed along a focal arc of a lens in reception, in [7] each of the receivers preferentially receives a signal from one incident direction. This means that in a standard
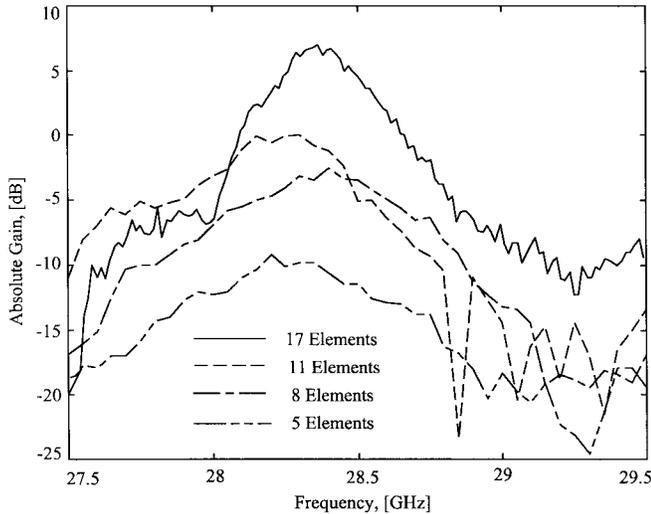
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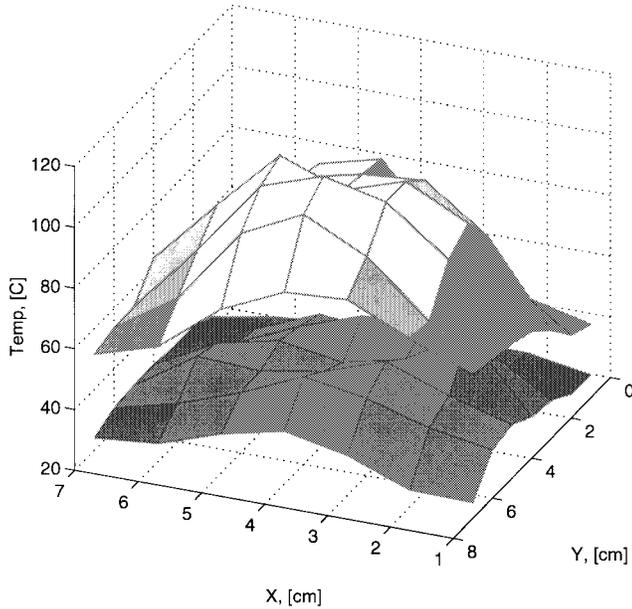
(b)

Fig. 12. (a) Successive measurements of lens subarray transmit gain as compared to a direct free-space link between two horn antennas. The different gains correspond to 5, 8, 11, and 17 unit cells populated with amplifiers. (b) Measured temperature profile for 17-element array with and without air cooling and at a dc bias of 4 V and 2.25 A.
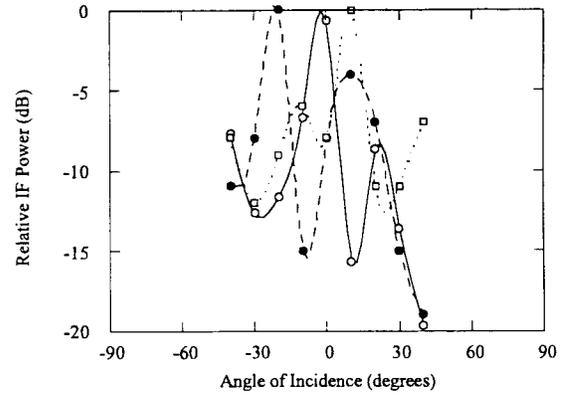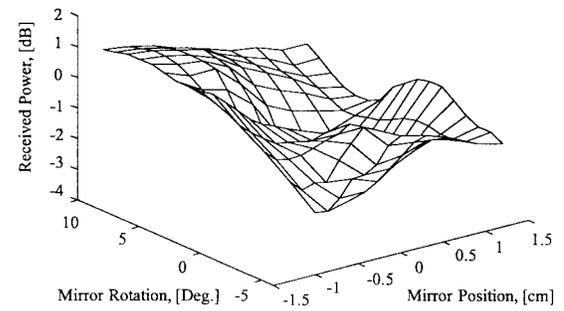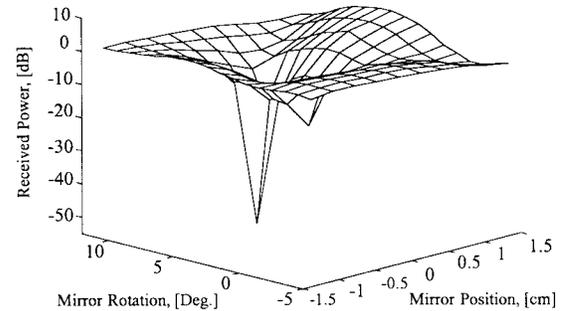

Fig. 13. Three received IF signals in a receiver with angle diversity. The three signals are measured at three mixers positioned along a focal arc, as a carrier source is moved in the far field [7].

(a)

(b)

Fig. 14. Measured maximum multipath fading nulls of a 10.1-GHz carrier signal (a) with and (b) without the 24-element lens amplifier array inserted. The received power is normalized to through measurements without the mirror inserted.

slow-fading communication channel [20], it is unlikely that incoming signals would simultaneously destructively interfere at all three receivers. As an example, in a Rayleigh channel with an order of diversity equal to three, if binary phase shift keying (BPSK) modulation is used, the probability of error for a given signal-to-noise ratio (SNR) decreases as $P_e \propto (3/\mathrm{SNR})^3$ [21].

Reduction of multipath fading using a single receiver and taking advantage of the directivity of a lens amplifier array can be demonstrated by a simple measurement [11] on the example of the bidirectional lens from Section II-B. A 45 cm × 30 cm metallic mirror located parallel to the optical axis in front of the amplifier array was translated in 3-mm steps perpendicular to the optical axis. For each step, the mirror

was rotated through a set of angles. The received power was measured for all mirror positions with and without the lens amplifier. The measured maximum fades of a 10.1-GHz carrier signal, with and without the 24-element lens amplifier, and normalized to the received signal without the mirror inserted, are shown in Fig. 14. Maximum fading nulls were improved (decreased) by about 45 dB in this case. (Notice the different vertical scales in the two plots.)

C. A Multiuser Frequency-Reuse QO Architecture

A multiuser frequency-reuse experiment demonstrates how two separate signals incident from different angles can be received independently at different locations along the focal
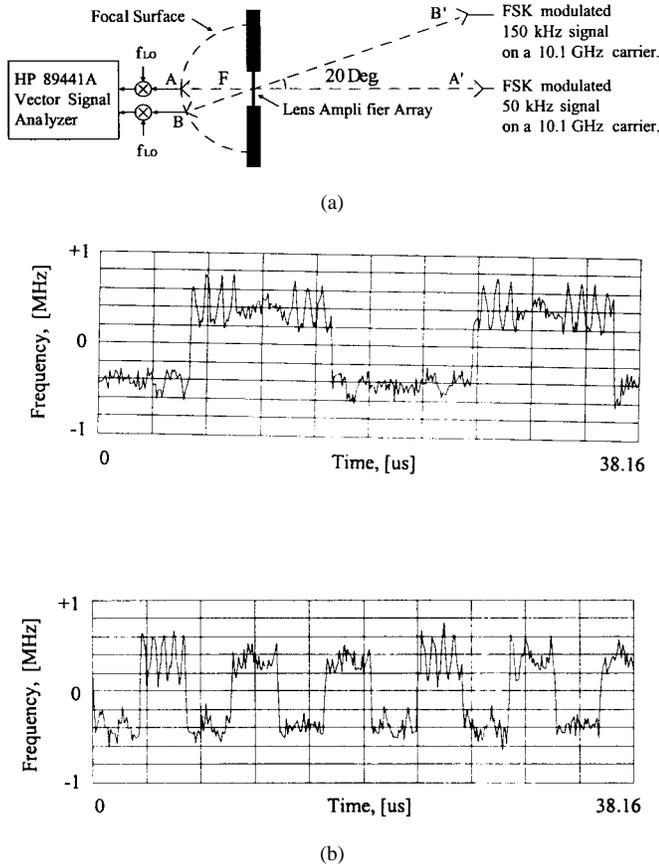
(a)

(b)

Fig. 15. (a) Test setup for the multiuser experiment. Square-wave signals at $f_A = 50$ kHz and $f_B = 150$ kHz are frequency modulated on a 10.1-GHz carrier and input at 0° and 20° from the optical axis, respectively. The two signals are received by horns located on the focal surface behind the 24-element lens amplifier array, and demodulated using a vector signal analyzer. (b) Received and frequency-shift keying (FSK) demodulated 50- and 150-kHz signals for receivers located at 0° and 20°, left and right, respectively.

Fig. 16. Beam scanning in H-plane at 10.1 GHz for the 24-element lens amplifier array in receive mode. Receive horn at (–) 0, (– –) −20°, and (· · ·) 20° locations are shown. The normalizing power levels of the main lobes are within 2 dB.

Fig. 17. A sequentially rotated two-element T/R array [14].

surface of the 24-element lens amplifier array. Two incident signals at 0° and 20° and with the same incident power levels, are used for the demonstration, as illustrated in Fig. 15(a). The received power of an interfering signal originating 20° from the desired signal has a measured relative power of about −10 dB in this setup. Square-wave signals at $f_A = 50$ kHz and $f_B = 150$ kHz are frequency modulated on a 10.1-GHz carrier and incident from 0° and 20°, respectively. The demodulated signals received at the 0° and 20° positions on the focal surface are shown in Fig. 15(b). The interfering signal appears as an additional ripple in the demodulated signal.

D. QO Architecture for Synthetic Aperture Radar

An example in which the QO architecture might be advantageous in radar is a mapping application, such as the shuttle imaging radar (SIRC). This 5-GHz synthetic aperture radar (SAR) flies at an altitude of about 200 km with a look angle of between 25°–50° in the azimuth direction. The antenna array is synthesized along the flight direction, and has about a 5° beamwidth in the look direction, with dual linear polarization. The transmitter is distributed in several hundred T/R modules that produce a total power of 1.5-kW peak with a 5% duty
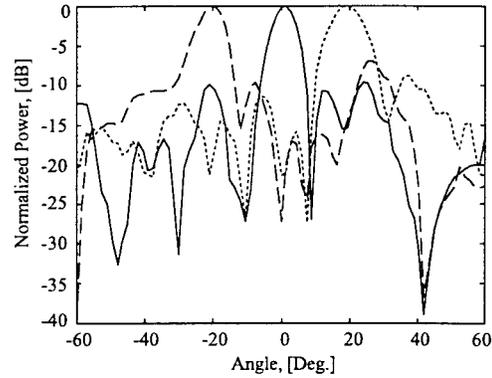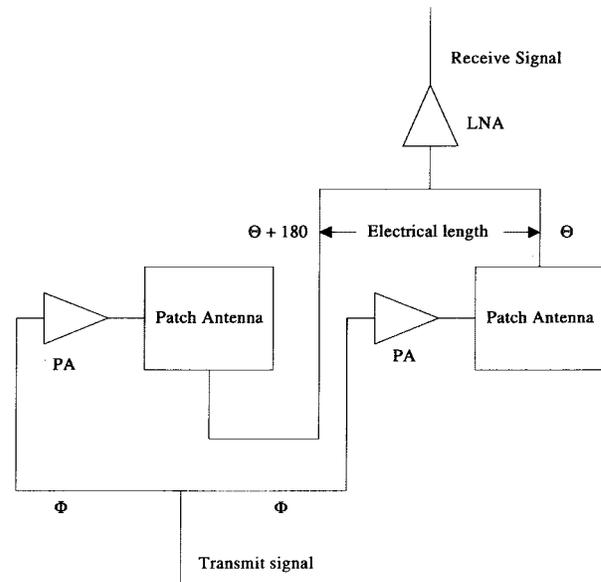
cycle. Circulators are currently used to isolate the T/R paths, but switches would probably be a better choice. The antenna beam needs to be steered discretely in the look direction to image a certain strip parallel to the velocity vector. Typically, 5–10 beams are required, and this is currently done with phase shifters [22].

A QO lens amplifier architecture can be envisioned for this application that would allow the free-space power combining in transmission, give good dynamic range in reception, with switching between T/R. In a lens amplifier, discrete beams can be steered with no phase-shifting circuits at the carrier frequency. In transmission, if the feed is moved along a focal arc, the main radiated beam shifts. Since often mechanical motion is not desirable, several feeds can be switched on at the low frequency, resulting in beam switching. Since the lensing effect is reciprocal, the same is true in reception. As an example, beam-steering patterns are measured at 10.1 GHz for receive locations at −20°, 0°, and +20° along the focal surface in the H-plane of the array from Section II-B, as shown in Fig. 16. This could easily accommodate 5–10 discrete beams
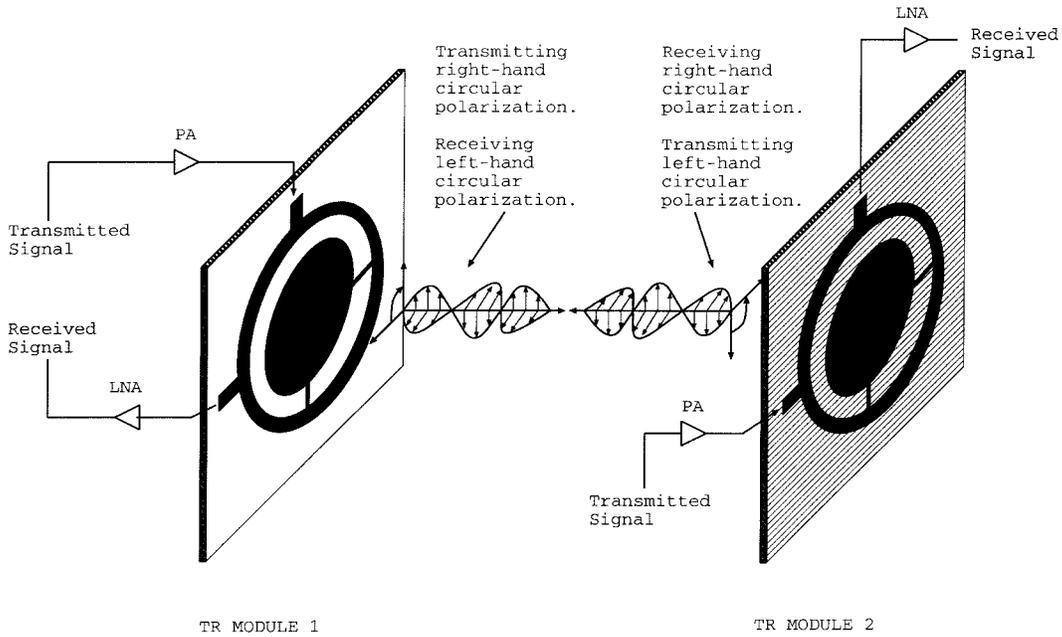
Fig. 18. Perspective view of a compact circularly polarized T/R antenna.

needed for SAR, especially at frequencies higher than X-band. Other applications where similar beam steering could be accomplished is in vehicular radar at 77 GHz where three discrete beams are required in reception, as well as "911" location in PCS communications (federal requirement for base stations).

E. QO Architecture for Missile Seekers

Another interesting radar application are missile seekers. The main motivation for using quasi-optics in this case is obtaining the required power of tens of watts in a compact package, but functionality such as T/R and beam steering is also needed. The current Ka-band systems typically take up a volume of a 15-cm-diameter aperture, about 20 cm in the other direction. The T and R directions are switched with a 25% duty cycle, with microsecond speed, and at least 30 dB of isolation, depending on the level the gates of the LNA's can tolerate. Both linear polarizations are received with the same antenna. The steering within about a 30° range is done mechanically currently, continuous or, in some cases, discrete with stepped overlapping beams [23]. Given the demonstrated results to date, a lens amplifier could perform these functions with a decrease in volume for a F/D ratio smaller than one, and an increase in reliability as discussed in Section IV.

IV. DISCUSSION

In this concluding section, we present several single antennas that would be suitable for integration into QO T/R arrays. We then discuss some general issues that will influence future developments, namely hybrid versus monolithic integration, reliability, and performance degradation as a function of device failure, thermal issues, power-combining efficiency, and combination with other technologies such as optics and microelectromechanical systems (MEMS).
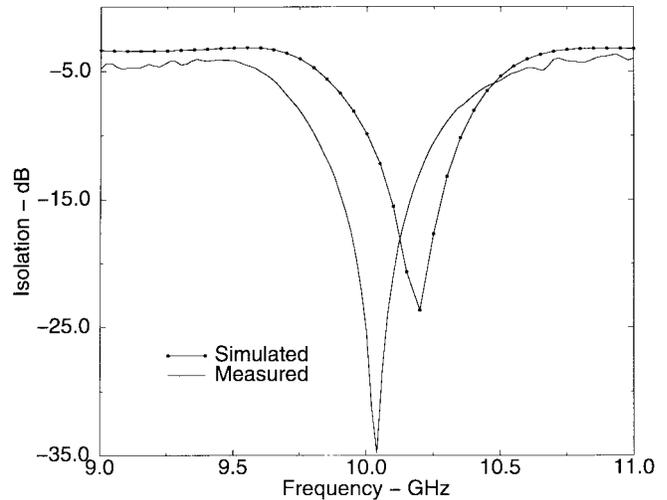

Fig. 19. Simulated and measured isolation between T/R ports of the antenna from Fig. 18.

A. Other Demonstrated Single Active T/R Antennas

Several T/R single active antennas have been demonstrated recently and are briefly described here. We feel these single elements are relevant to our discussion since they can easily be envisioned as elements of large arrays. Also, some applications, such as mobile hand-held units, vehicular radar and toll booth systems, require sufficiently low-power levels that can be accommodated with a single active T/R antenna.

One of the important factors that controls the range in full duplex is the isolation between receive and transmit ports. In [14], a modification of the approach described in Section II-A is used in a singe active antenna to improve the isolation between the T and R ports. This is accomplished by constructing a two-element active T/R array using dual linear polarization and sequential rotation. Two orthogonal ports of
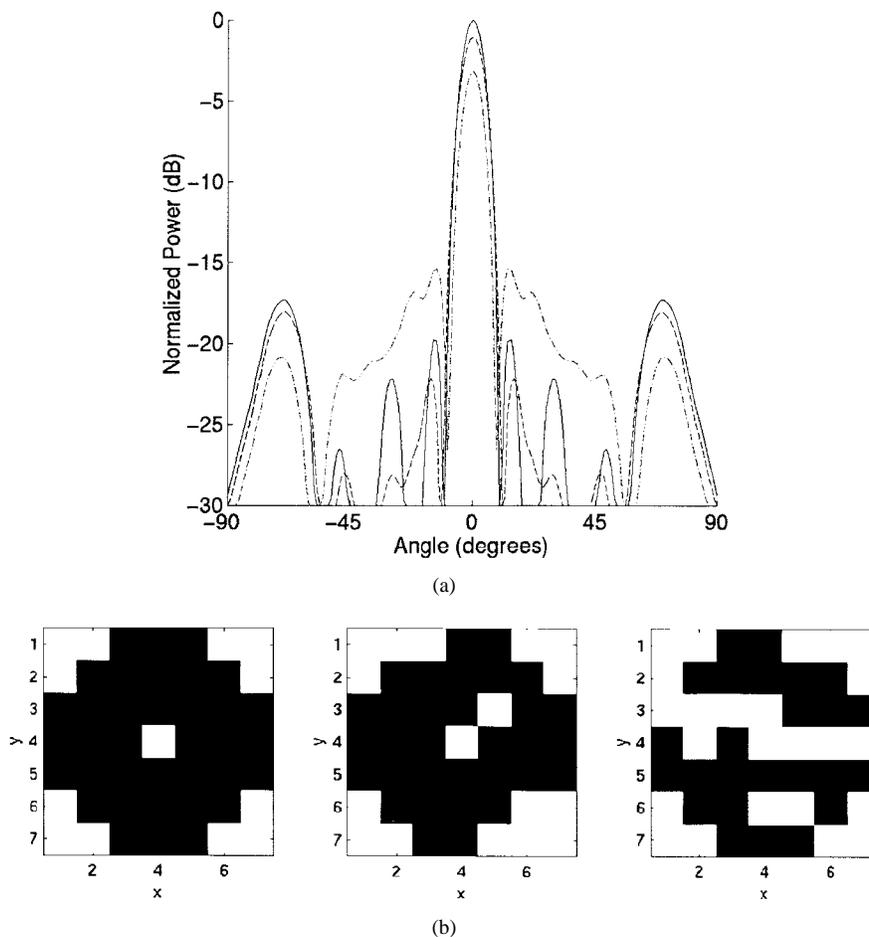
Fig. 20.   (a) Simulated radiation pattern as 10% (dashed line) and 30% (dotted line) elements fail randomly across the Ka-band lens array from Section II-C. (b) The white blocks show which elements in the array are simulated as failed in the two cases. The solid line shows the antenna pattern of the fully functional array, with the white square in the middle indicating the feed element in the folded focus approach.

two microstrip patch antennas are used for T/R ports. A circuit-level combiner is used to combine the received signal from two patch antennas while canceling the leakage from the transmit ports, as shown in Fig. 17. The isolation between the receive and transmit ports is better than 45 dB. Also included in [14] are link budget calculations to determine the size of the T/R array which is necessary for a given range requirement.

The integration of two antennas into a single antenna serves to reduce the circuit size and to simplify the design process. One may also be able to eliminate T/R switches that have approximately 1.5–2 dB of loss at millimeter wavelengths. In addition, in some applications, such as wireless LAN's and satellite communications, circular polarization is preferred to linear. A circularly polarized microstrip T/R antenna is shown in Fig. 18 [15]. This figure illustrates the single antenna surrounded by a 90°/180° hybrid. In this way, a two-port network capable of transmitting and receiving a left-hand-side and right-hand-side polarized signal is created. Ideally, one should be able to achieve large enough isolation between the receive and transmit ports necessary for full duplex operation. The signal injected into the transmitting port of TR module "1" in Fig. 18 is radiated with a right-hand-side polarization. The receiving port is isolated from the transmitting port by way of the hybrid network. The left-hand-side circularly polarized

signal transmitted by T/R module "2" will be directed to the receiving port of T/R module "1." The figure also shows further size reduction in the circuit by placing the patch antenna within the hybrid network. Fig. 19 shows the simulated and measured isolation between the T and R ports.

B. Other Considerations

From the above examples, we conclude that a QO approach has potential advantages for T/R front ends compared to conventional approaches, especially at millimeter-wave frequencies. Of course, significant research and development is required before this can be quantified. Many questions are left unanswered, e.g., is a hybrid architecture preferable over a monolithic one? With the advancement and commercial availability of MMIC's at lower millimeter-wave frequencies, it is likely that a hybrid approach could be lower cost. However, there are disadvantages of using MMIC's—one is confined to a 50-Ω environment, which is often not the best choice for circuits integrated with antennas, and the bias pads are located so that an array biasing network is hard to design. On the other hand, the reliability across a monolithically fabricated array at centimeter wavelengths needs to be good, which is not be easy to achieve.

The main advantages of the QO approach are improved reliability and high-power-combining efficiency in both T and R modes. The reliability should be high due to the distributed architecture. For example, in the amplifier array from Section II-C, Fig. 20 shows the pattern degradation when 10% (dashed line) and 30% (dotted line) of the elements, randomly distributed across the array fail, normalized to a uniform array with a triangular lattice.

The combining efficiency is expected to be independent of the number of elements. This can be estimated from single amplifier measurements [24] and [25], where combining efficiencies of 85% and 75% were reported, respectively. Therefore, the QO approach has merit for transmitters in which it is advantageous to use a large antenna array with power requirements that can be achieved by combining many lower PA's. In such a case, for the same number of amplifiers, the power-combining efficiency of a standard combiner is too low. For example, for 0.5 dB of loss per combiner, 60% efficiency is reached at four combiner stages by employing conventional circuit combiners [6].

Two of the T/R array described in Section II used semiconductor (p-i-n or MMIC) switches to route the signal. The new developments in MEMS switches have demonstrated 0.25-dB loss at 35 GHz with 35-dB isolation and 2-μs switching speeds with several terahertz cutoff frequencies [26]. This is not fast enough for most T/R applications, which require typically less than 50-ns speed, but in some cases, such as SAR [22], microsecond switching speeds are sufficient. Furthermore, the design of future QO T/R arrays can take advantage of optical techniques for switching, remoting, or beam control. For many T/R applications, adaptive beamforming is either required or could offer substantial improvements. The QO approach, in particular the lens amplifiers, can be used to perform a part of the adaptive signal processing at the analog front end without additional hardware, as has been crudely demonstrated in [7]. A more advanced study is required to demonstrate the usefulness of this concept.

In summary, this paper presents new architectures for T/R modules associated with relatively large antenna arrays. These architectures are distributed in both transmitter and receiver, and the signals are coupled to the distributed amplifiers through free space on both the radiating and feed sides. Several demonstrations were presented at X- and Ka-bands, and possible advantages of using these architectures for different applications were discussed. In order for this technology to be practical, the following remains to be researched and demonstrated:

1) power-combining efficiency as a function of the number of transmitters;
2) reliability and performance degradation characteristics;
3) beam-forming and beam-steering capabilities;
4) ways to achieve high isolation between T/R in switched and full duplex systems, respectively.

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