Progress in Active Integrated Antennas and Their Applications

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(Invited Paper)

***Abstract*— Active integrated antennas (AIA's) provide a new paradigm for designing modern microwave and millimeter-wave architecture with desirable features such as compactness, light weight, low cost, low profile, minimum power consumption, and multiple functionality. This paper reviews recent research and development related to this emerging technology with emphasis on its applications in high-efficiency radio-frequency (RF) front-end, millimeter-wave power combining, beam steering, and retrodirective arrays, as well as wireless sensors. Optical controlling techniques for AIA's are also described.**

***Index Terms*—Active integrated antenna, phased array, power amplifier, power combining, quasi-optics, retrodirective array, transponder, wireless.**

I. INTRODUCTION

ACTIVE integrated antennas (AIA's) provides a new paradigm for designing modern microwave and millimeter-wave architecture for both military and commercial applications. From the microwave engineer's viewpoint, an AIA can be regarded as an active microwave circuit in which the output or input port is free space instead of a conventional 50-Ω interface. The antenna is not only used as a radiating element, but also provides certain circuit functions such as resonating, filtering, and diplexing, and is an integral part of the microwave circuit design. On the other hand, from the antenna designer's point-of-view, the AIA is an antenna which possesses built-in signal and wave processing capabilities such as mixing and amplification. A typical AIA consists of active devices such as Gunn diodes or three-terminal devices to form an active circuit, and planar antennas including printed dipole, microstrip patch, bowtie, or slot antenna.

One of the most prominent features of the AIA is that the antenna and active device are treated as a single entity. This differs from the design methodology of conventional wireless systems, where the antenna and radio-frequency (RF) front-end are separate components, which are connected by a 50-Ω transmission line or standard waveguide. The tight and intelligent integration of the antenna and active circuit within an AIA makes possible innovative microwave and millimeter-wave application systems with desirable features such as compactness, low cost, low profile, minimum power consumption, and a high degree of multiple functionality.

Historically, the concept of the AIA was proposed and employed in the design of quasi-optical mixers with an aim of either eliminating the lossy and bulky interconnect between the device and antenna [1] or taking full advantage of some intrinsic properties of the antenna, such as polarization duplexing [2]. Recently, the AIA concept has been extensively employed in the area of quasi-optical power combining, which was proposed originally to combine the output power from an array of many solid-state devices in free space to overcome the power limitations of individual devices at millimeter-wave frequencies [3], [4]. In fact, the development of novel efficient quasi-optical power combiners has been one of the major driving forces for the research on AIA's during the past ten years [5], [6].

Since our last review [5], numerous innovative designs based on the AIA concept have been proposed and successfully demonstrated. AIA technology has evolved to a point where practical implementation into the latest microwave and millimeter-wave systems is considered feasible and pursued currently in a number of related fields such as power combining, beam steering and switching, as well as retrodirective arrays. These AIA-based designs are particularly attractive for millimeter-wave systems because they provide an effective solution to several fundamental problems at these frequencies, including higher transmission-line loss, limited source power, reduced antenna efficiency, and lack of high-performance phase shifters.

This paper reviews recent research activities related to this emerging technology with emphasis on its applications in high-efficiency RF front-ends, millimeter-wave power combining, beam steering, and retrodirective arrays, as well as wireless sensors. Optical controlling techniques for AIA's are also discussed. For those who have not closely followed the development in this area, we would like to refer to [5], where a more detailed description of the constructing elements of AIA's, as well as some application examples, were described.

II. HIGH-EFFICIENCY POWER AMPLIFIERS

High-efficiency power amplifiers are always key components in wireless communication systems. For example, improving the power-added efficiency (PAE) of an onboard 2-kW solid-state power amplifier (SSPA) in a communication satellite from 25% to 30% will reduce the waste heat

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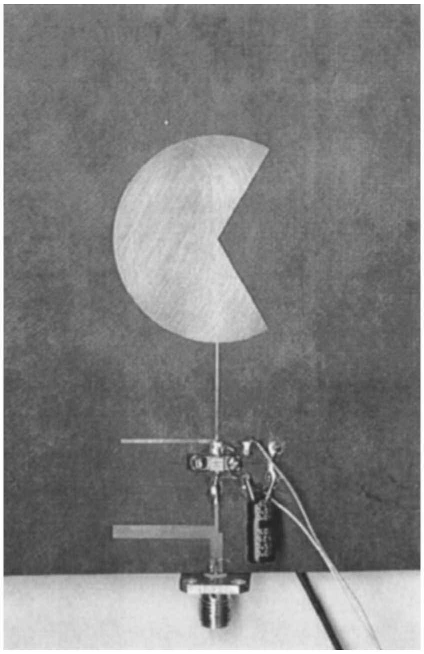


Fig. 1. A class-F power amplifier integrated with circular sector microstrip antenna [9].

substantially from 6 to 4.7 kW [7]. Therefore, even a few percent improvement in PAE is considered significant if it can be achieved without introducing major linearity degradation and greatly increasing the circuit complexity.

Recently, the concept of the AIA has been employed in an effort to design high-efficiency microwave power amplifiers. In this approach, the antenna element is used not only for radiation to form a desired beam, but also as a part of the tuning circuit to appropriately terminate the harmonics at the output port of the amplifier.

The first demonstration was a class-B GaAs FET power amplifier integrated with a patch antenna, which is shorted in the middle so that the input impedance at the second harmonic becomes zero because of the elimination of the TM_{20} mode. This resulted in a 7% improvement in the PAE, and an increase of 0.5 dB in the output power when compared to a reference amplifier using a standard patch antenna without shorting pins [8].

A more recent design employed a modified circular segment microstrip antenna, which is capable of reactively terminating both the second and third harmonics. Fig. 1 shows a class-F amplifier based on this design approach. There is no "reference" antenna for comparison in this case. A relatively high PAE of 63% was achieved at 2.55 GHz. The measured output power was 24.4 dBm. No major degradation in the antenna radiation patterns was observed with the cross-polarization level below -16 dB at all directions in both the E- and H-planes [9].

III. QUASI-OPTICAL POWER COMBINING

Increasing demand for millimeter-wave radar and communication systems has created the need for high-power solid-state transmitters. Great effort has been spent on developing monolithic integrated circuits at frequencies up to W-band. Using the latest 0.1-μm pseudomorphic high electron-mobility transistor (pHEMT) technology, for example, a single-chip power amplifier with 300-mW output power at 94 GHz has been recently demonstrated [10]. However, a millimeter-wave radar will typically require transmitting power of a few watts or higher. In parallel with developing new material and device technology, quasi-optical power combining has been considered one of the most promising approaches to overcome the power limitations of current solid-state devices, making available SSPA's which are comparable or superior to conventional traveling-wave tube amplifiers (TWTA's) [3]–[6].

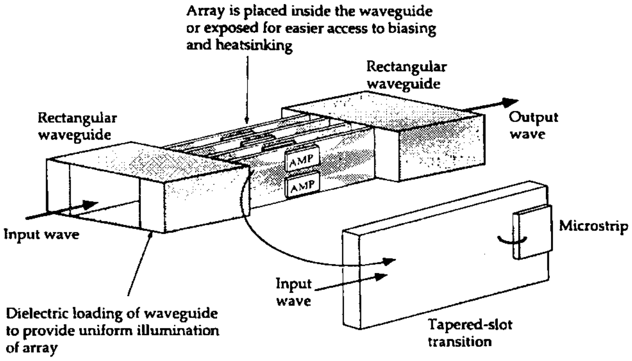


Fig. 2. A quasi-optical traveling-wave amplifier array placed between X-band waveguides [28].

Many innovative approaches have been proposed for realizing efficient quasi-optical power-combining arrays. Among them are wave beam arrays [4], grid arrays [11]–[14], patch-based arrays [15]–[19], slot-based arrays [20]–[23], and monopole-probed-based arrays [24], [25]. Bidirectional amplifier arrays with both transmitting and receiving capabilities have also been recently demonstrated [26], [27]. One common feature of these power combiners, whether oscillator- or amplifier-type, is that they are three-dimensional (3-D) structures where power combining is realized through free space in order to eliminate transmission line or waveguide losses. Due to tight real-estate limitations for a two-dimensional (2-D) array on a semiconductor wafer, the concept of an AIA has been extensively employed to realize compact lightweight power combiners, which must satisfy simultaneously stringent requirements, including acceptable input–output isolation, good impedance matching, tolerance to alignment errors, and minimum sensitivity to operation instabilities.

One remaining technical challenge for these 3-D power-combining structures is the thermal management issue, especially when a large-scale array with high levels of continuous wave (CW) output power is to be designed. To ease this problem, a waveguide-based spatial combining scheme using broad-band tapered-slot transitions with good thermal properties was recently proposed [28]. Fig. 2 shows the X-band prototype consisting of a 2 × 4 array of medium-power GaAs monolithic microwave integrated circuits (MMIC's), which produced an output power of 2.4 W and 9-dB power gain at 1-dB compression, with a combining efficiency of 68% and less than 1-dB gain variation over the full waveguide band (8–12 GHz). To increase the device packaging density and avoid

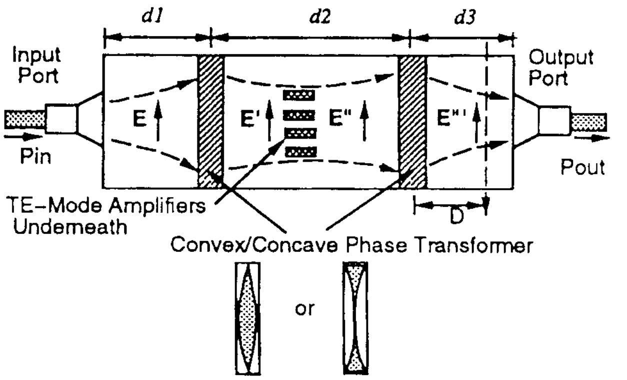


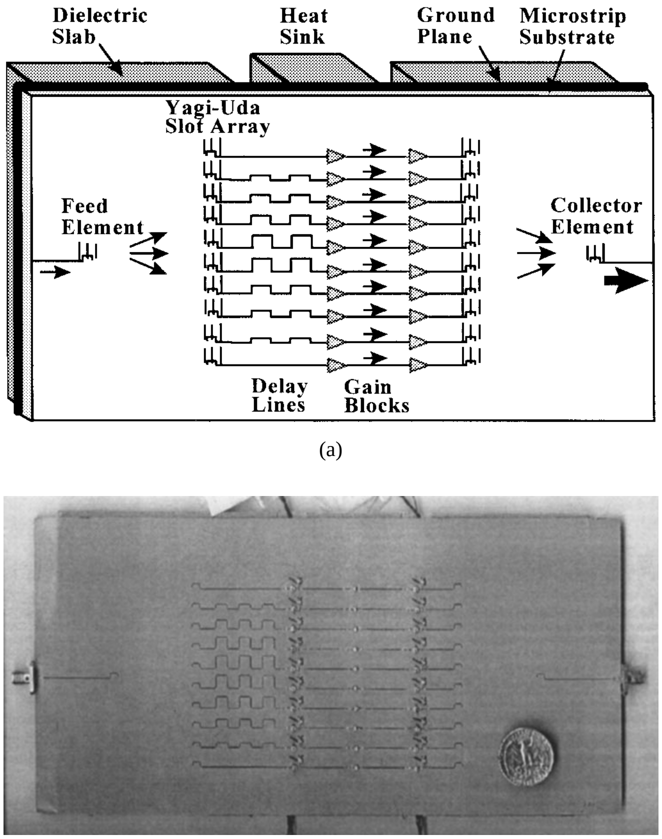
Fig. 3. A TE-type DSBW power-combining system with a linear array of four amplifiers underneath the dielectric slab [34].

the lower frequency cutoff by the rectangular waveguide, a coaxial combiner capable of accommodating a radial array of 64 elements has also been proposed [29].

Recently, a radically new concept of quasi-optical power combining using dielectric slab-beam waveguides (DSBW's) was proposed [30]–[37]. In contrast to all the previous power-combining structures, this is a 2-D system, which takes advantage of the unique propagation characteristics of a hybrid surface wave/confined Gaussian–Hermite beam modes within a dielectric slab [30]. The resultant power combiner is planar and more amenable to MMIC technology. However, the most significant advantage of this new design architecture is that it provides a fundamental solution to the heat-dissipation problem, which is persistent in most of the previous structures. In fact, a properly designed 2-D combiner can simplify the thermal management issue to that for a single-device amplifier, as will be shown below.

Fig. 3 shows a TE-type 2-D quasi-optical power-combining amplifier, as reported in [34]. This structure confines a Gaussian beam mode within the dielectric where the signal is focused by either convex or concave phase transformers. The signal is amplified by an amplifier array that is placed underneath the dielectric. A peak gain of 19.5 dB at 7.23 GHz and an insertion loss of 3.5 dB was measured for this four-element amplifier array.

A TM-type planar dielectric quasi-optical (PDQ) power combiner has also been recently proposed and demonstrated [35]. Fig. 4 shows the schematic as well as X-band prototype of a ten-element PDQ power combiner. A key component in this design is the microstrip-fed Yagi–Uda slot-array antenna for unidirectional high-efficiency excitation of the dominant TM surface wave inside the grounded dielectric slab. The linear array of power devices can be placed on top of a solid metal block to provide a natural way for heat dissipation. An amplifier gain of 11 dB at 8.25 GHz with a 3-dB bandwidth of 0.65 GHz was measured. The design concept was confirmed by extensive numerical simulations [36], and development of a W-band PDQ power combiner is currently being pursued. Meanwhile, an alternative TE-type PDQ power combiner using printed dipole antennas was also designed [37]. An uncommonly large bandwidth of 56% with system gain greater that 7 dB has been demonstrated.



(a)

(b)

Fig. 4. (a) Schematic diagram. (b) X-band prototype of a ten-element PDQ power combiner [36].

IV. BEAM-STEERING ARRAYS

The various quasi-optical power-combining techniques described in Section III provide a practical means of obtaining medium- or high-power sources at millimeter waves in the near future. On the other hand, another important objective of the AIA is to realize power-combining arrays with built-in beam-steering capabilities. In [38], Stephan analyzed an array of inter-injection-locked oscillators and demonstrated that a progressive interelement phase shift could be established by injecting two coherent reference signals with a predetermined phase shift into the two end elements of the array. The most significant indication of this concept is the possibility of realizing beam-steering arrays without requiring phase shifters, which are considered indispensable in conventional systems. This novel approach is especially attractive at millimeter-wave frequencies where ferrite-based phase shifters and related feeding network can be lossy, bulky, and extremely costly. Other related applications such as active beam switching [39] and polarization control [40], [41] have also been proposed and demonstrated.

While the approach of controlling the coupling phase of the end elements, as shown in [38], might suffer from limited scan range for arrays of large size, an improved approach, which tunes the free-running frequencies of the two end oscillators in a linear array, was proposed by York [42]. Several power-combining and beam-steering arrays based on

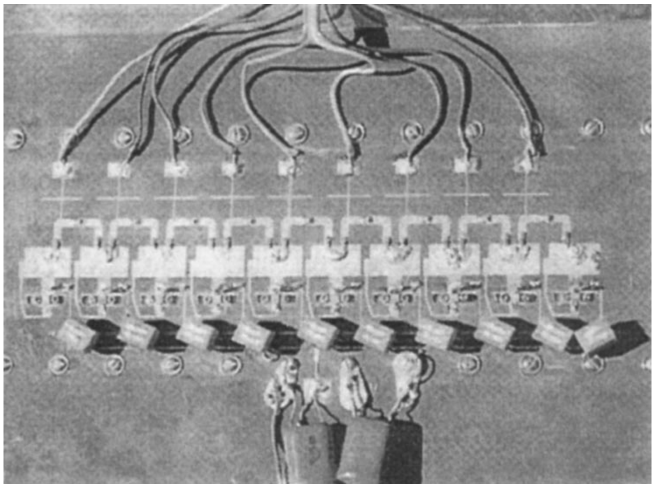


Fig. 5. Photograph of a ten-element power-combining and beam-scanning array using coupled VCO's [45].

this concept, both linear [43]–[46] and 2-D [47], have been successfully demonstrated. Fig. 5 shows the X-band prototype of a ten-element power-combining and beam-scanning array using coupled voltage-controlled oscillators (VCO's) [45]. A varactor-tuned patch antenna is used both as a load and frequency-selecting network for the feedback oscillator. Besides a measured effective radiated power (ERP) of 10.5 W at 8.4 GHz, a maximum scan angle of 30° is achieved. This scan angle corresponds to over 500° of phase shift over the array, indicating that the beam-scanning technique is not limited by the number of array elements.

Two major issues of concern related to this type of beam-steering arrays are the phase-noise performance and possible multimode operation. A detailed investigation of the phase noise in mutually synchronized oscillator systems indicates the necessity of using low-noise external injection sources in order to satisfy the system requirement in most practical applications [48]–[50]. Meanwhile, a stability study reveals that the steady-state phases in coupled oscillator arrays are dependent not only on the free-running frequency distribution, but also on the coupling-phase angle [42]. In [51], the problem of multimoding in a strongly coupled oscillator array is analyzed by using the average potential method. An approach for mode stabilization using resistors as mode suppressors was proposed and demonstrated [52].

To simultaneously satisfy the requirements for low phase noise and stable single-mode operation in practical systems, a beam-steering array using unilateral injection locking has been designed and demonstrated by Lin *et al.* [53]. Recently, Nogi *et al.* proposed an alternative approach, which is capable of increasing the scanning range while simultaneously avoiding mode jumping [54]. Fig. 6 shows the schematic diagram of a five-element array based on this new design concept. The two end elements are locked by an external injection signal with a certain phase relation, which is similar to the structure originally proposed in [38]. However, by tuning the free-running frequency of one of the end elements, stable single-mode operation is realized even for the case of relatively large interelement phase shift.

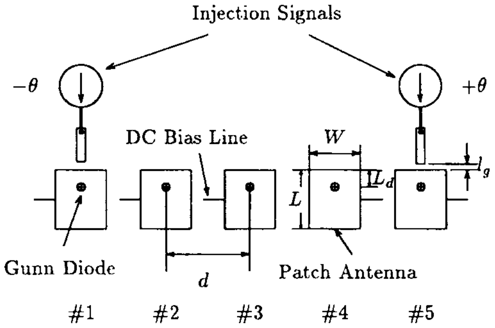


Fig. 6. Schematic diagram of an injection-signal controlled active phased array with a frequency-shifted end element [54].

V. OPTICALLY ASSISTED AIA'S

Recent progress in semiconductor laser sources [55], fiber optics, and photonic devices [56] has made possible such applications as antenna remoting in cellular and microcellular radio systems using analog fiber links [57], distribution of cable-television signals [58], and beam forming for phased-array antennas [59]. The introduction of photonic devices and fiber optics into microwave and millimeter-wave systems provides several advantages, such as more compact design, reduced insertion loss, immunity to electromagnetic interference (EMI), and additional degrees of freedom in controlling the RF circuits. While several different techniques can be used for microwave-optical interaction, here, we consider two approaches of optically assisted AIA's. One is the optical control of active devices by direct illumination. The second application is remote control of active phased array using fiber-optic links.

It is well known that the electrical characteristics of solid-state devices such as FET's can be controlled by optical illumination. In [60], this phenomenon was used to tune the operating frequency of a two-element power-combining array with strong coupling. An optical tuning range of 70 MHz around 8.8 GHz was achieved by changing the intensity of optical illumination on the FET chips. More recently, optical illumination and control of MESFET transistors in an active phased array was demonstrated [61]. Fig. 7 shows the photograph of a two-element beam-scanning array based on unilateral injection locking [53]. To prevent the illumination source from disrupting the antenna patterns, the two MESFET's are mounted through the substrate and illuminated from the backside of the circuit. A frequency-tuning range of 20 MHz and a beam scan of 20° was achieved. To increase the frequency-tuning range and improve the beam-scanning capability, a quasi-optical oscillator with optically controlled varactor was designed and tested [62]. The new design achieved a twofold improvement in tuning bandwidth, and negligible change in output power as a function of oscillator phase.

Another application of interest is the remote control of an AIA array by optical means. The use of fiber-optic links for antenna remoting is a very attractive approach because of the highly conformable, lightweight, low loss, and EMI-free properties of the optical fiber. Fig. 8 shows the schematic

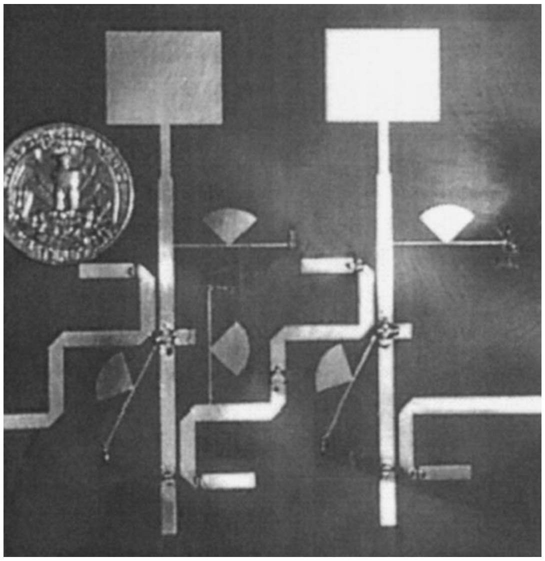


Fig. 7. A two-element beam-scanning array based on unilateral injection-locking and optical control of free-running frequencies [61].

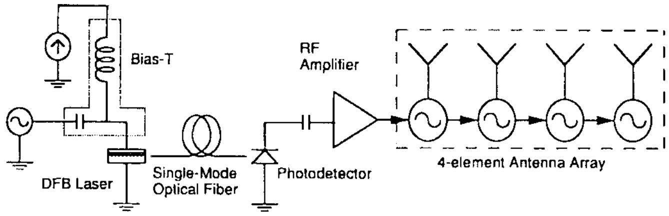
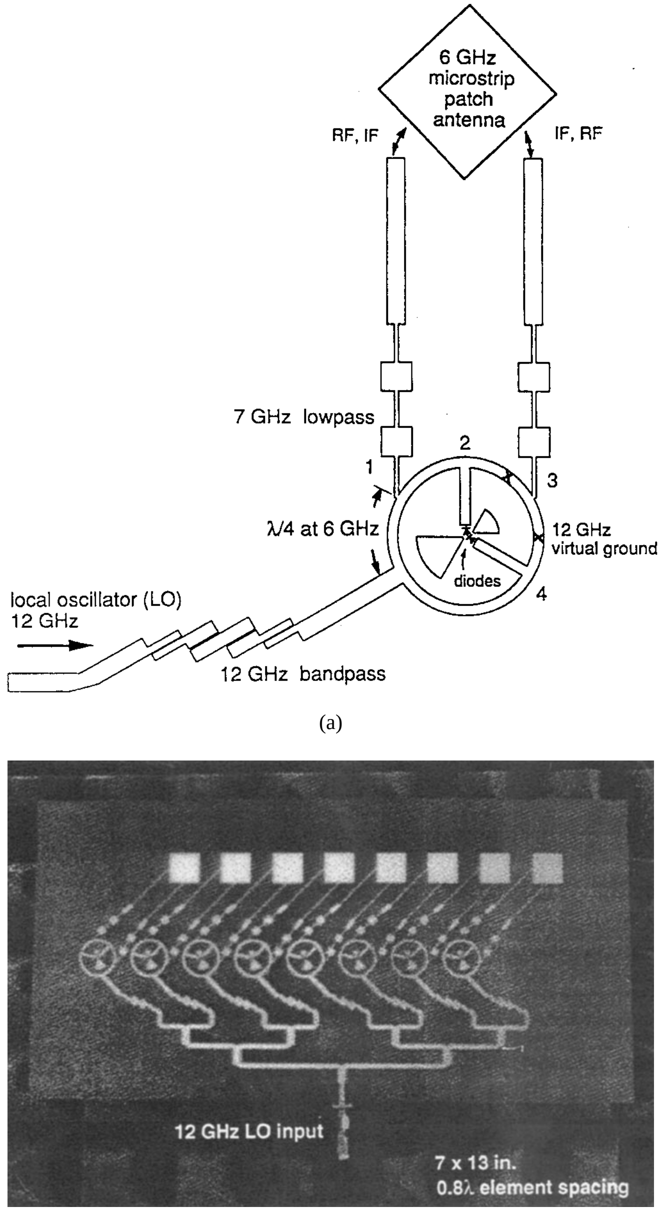


Fig. 8. Schematic diagram of an active phased array with optical input and beam-scanning capability [63].

diagram of an active phased array with optical input and beam-scanning capability [63]. The microwave reference signal for injection locking is fed remotely through the optical fiber. The RF signal is first converted into an optical signal by directly modulating a multiquantum-well InGaAs-InGaAsP distributed feedback (DFB) laser, and then launched into a single-mode optical fiber. At the antenna platform, the reference microwave signal is recovered by a high-speed photodetector followed by an amplifier. By tuning the free-running frequencies of a four-element unilateral injection-locked oscillator array, a scan angle of about 21° was measured. A remotely controlled 2 × 2 active antenna array with beam-switching capability in both azimuth and elevation planes has also been demonstrated [64]. Furthermore, in [65], a gain-switched laser diode was used both as a RF-to-optical converter and RF frequency doubler in designing a Doppler transceiver array with optical remote control. The second harmonic signal generated from the nonlinearities of the laser was used as the reference signal for injection locking to ensure in-phase operation of the transceiver array.

VI. RETRODIRECTIVE ARRAYS

Retrodirective arrays represent a type of special antenna, which reflect any incident signal primarily back toward the source without prior knowledge of the source's location. From the antenna point-of-view, a retrodirective array has an omnidirectional coverage, while simultaneously maintaining a high level of antenna gain. This unique property makes retrodirective arrays important in a wide range of applications, such as self-steering antennas, radar transponders, search and rescue, and noncontact identification systems [66], [67].



(a)

(b)

Fig. 9. (a) Heterodyne-phased scattering element. (b) Eight-element retrodirective array [72].

To realize retrodirectivity, each element in the array must radiate an outgoing wave whose phase is conjugate to that of the incoming signal relative to a common reference [68]. One of the most well-known retrodirective arrays is the Van Atta array, where conjugated elements of a symmetric array are connected by transmission lines of equal length [69]. To overcome the limitations on symmetry of the array and uniformity of the phasefront in the Van Atta array, a more general approach of phase conjugation based on heterodyne mixing was proposed [70], [71]. By mixing the incoming signal with a

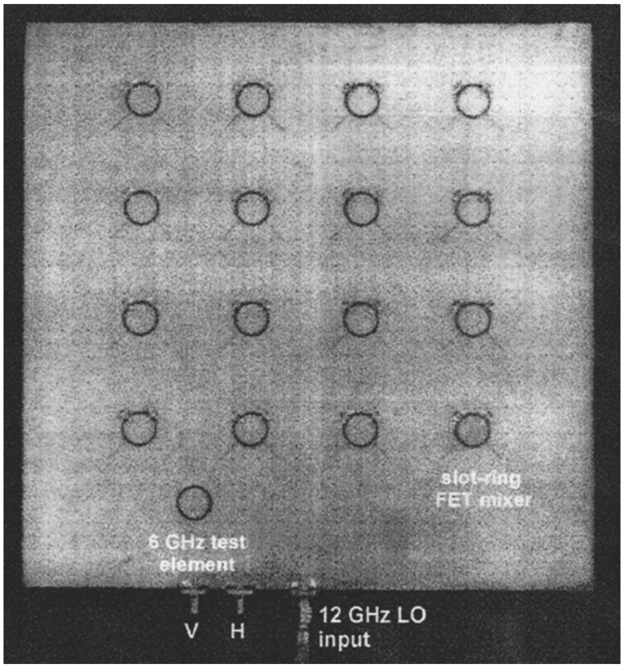


Fig. 10. A 2-D retrodirective array using ring slot antennas [74].

local oscillator (LO) signal at twice the frequency, the original frequency is obtained as the lower sideband product, but the resulting phase is inverted. Since phase conjugation occurs directly at each element, this approach allows irregular element spacing and nonplanar arrays, which are attractive features when antennas conformal to the surface of an aircraft fuselage or automobile must be designed.

The greatest challenge in designing mixers for retrodirective arrays is the separation of input and output signals, which correspond to the RF and intermediate frequency (IF) of the mixer, respectively, but share the same frequency. Since filtering is impossible, alternative approaches of RF/IF isolation are required. Fig. 9(a) shows a novel heterodyne-phased scattering element using a square patch antenna, and a modified "rat race" mixer where the LO and IF are interchanged so that effective RF/IF isolation is realized [72]. Fig. 9(b) shows a prototype eight-element linear array based on this design, which operates at 6 GHz (12-GHz LO). The array is capable of redirecting the interrogation signal back to its source for any angle of incidence and any type of polarization, linear and circular of either rotational sense. Similar designs of two-element retrodirective arrays using power dividers or dual-polarized patch antennas have also recently been reported by Karode and Fusco [73].

Meanwhile, a 2-D version of the above-mentioned conformal retrodirective array is desirable to further increase its range of applications. Fig. 10 shows a 4 × 4 retrodirective array based on slot ring antennas [74]. Each array element comprises a balanced FET resistive mixer integrated in a ring slot, which serves as both the radiating antenna and hybrid for RF/IF isolation. The backscattering pattern of this array exhibits over 100° scan range in both azimuth and elevation planes. Details of this structure can be found in [74].

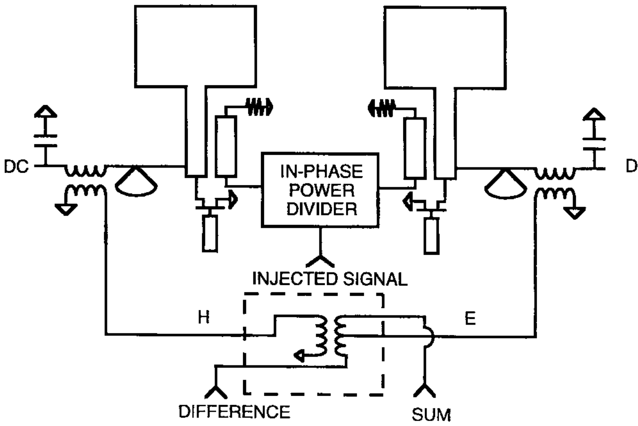


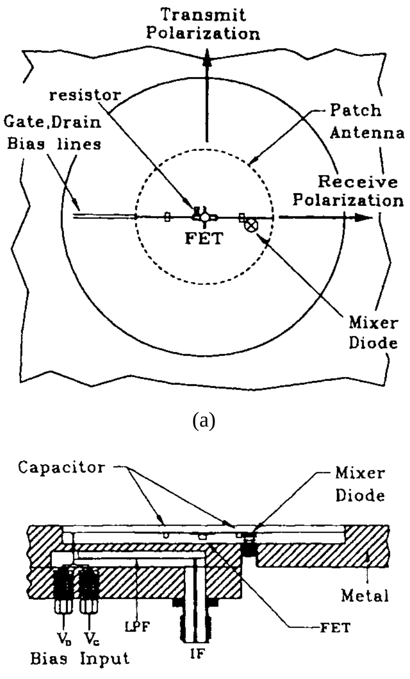
Fig. 11. A planar Doppler radar transceiver module with azimuth tracking capability [77].

VII. TRANCEIVERS AND TRANSPONDERS

Explosive growth in the area of wireless communications and RF sensors in recent years has created strong demand for inexpensive high-performance circuits and systems operating at frequencies from UHF to millimeter waves. Transceivers for wireless local area networks (WLAN's), transponders for remote identification of personnel and articles, and millimeter-wave vehicle radars for intelligent cruise control are just a few of the numerous application examples. Some of the key requirements in designing these wireless systems include small size, low cost, light weight, and minimum power consumption [75].

The AIA is an ideal candidate for designing compact transceivers and transponders for these wireless applications because of the possibility of building the whole RF subsystem, including oscillator, amplifier, antenna, and mixer onto a single dielectric substrate. In one of the earlier designs [76], an X-band quasi-optical transceiver element was realized by using the FET as both signal source and self-oscillating mixer for down-conversion of the received signal. Since the IF signal corresponds to the Doppler-frequency shift, a simple, compact, and lightweight motion sensor is obtained. Recently, this concept was applied to a two-element microstrip patch array, which uses the injection-locking beam-switching technique to function as a Doppler radar with azimuth-tracking capability [77]. As shown in Fig. 11, this transceiver module uses two MESFET's as both transmitting oscillators and self-oscillating mixers to obtain the IF (Doppler shift frequency) signals. A sum pattern is transmitted at 6.5 GHz, and both sum and difference signals are available at IF, which provide the range-rate and rough azimuth of a moving target. An initial test shows that the radar can be a promising alternative to conventional systems using Gunn oscillators and horn antennas.

Fig. 12 shows another compact low-cost AIA transceiver suitable for two-way communication links [78]. The design used an inverted circular patch as the antenna. An FET generates the transmitted carrier, which is also used as the LO for conversion of received signals via a diode mixer integrated to the patch. The receive pattern is perpendicular to the transmit pattern for LO-to-RF separation. A two-way



(a)

(b)

Fig. 12. An AIA transceiver using Schottky diode mixer and inverted patch antenna. (a) Top view. (b) Side view [78].

communication system using these novel transceivers was demonstrated, with a predicted maximum range of 4.8 km for the case of a 6-MHz-wide channel.

A transponder is a circuit which, when triggered by an external interrogation source at a predefined frequency, will transmit a response signal to the interrogator, preferably at a different frequency for the purpose of interference reduction. The use of small low-cost microwave "tag" transponders for noncontact identification such as entry systems, toll collection, and inventory control has attracted much interest in recent years. Fig. 13 shows the schematic diagram, as well as photograph of a 6-GHz noncontact ID card based on a subharmonically pumped quasi-optical mixer using a broad-band bowtie antenna [79], [80]. When illuminated by a 6-GHz interrogating signal, it transmits a unique digital identification code at the response frequency near 12 GHz. By upconverting the digital ID code signal to variable frequencies, multiple cards can be read simultaneously. Since the response is nonharmonically related to the interrogating signal, the possibility of false detection is minimized. Another unique feature is the use of a slot antenna coupled with a rectifying diode to trigger the card from its standby state. The standby and operating currents are 25 μA and 1 mA, respectively, from a +1.5-V silver oxide battery. Reducing the standby current to 1 μA could increase the current one-to-two-year battery life to approximately ten years, assuming that the card is interrogated daily for 1-min [80].

Another example of low cost, compact, and planar transponder design is the frequency-doubling integrated push–push active microstrip transponder [81], as shown in Fig. 14. In addition to receiving the input signal, the receiving microstrip antenna also divides the power into two equal parts and produces a phase shift of 180° between the two output ports. This eliminates the need for phase shifter and power divider between the active devices and receiving antenna. Using two nonlinearly biased MMIC amplifiers, an effective conversion gain of up to 6 dB has been successfully demonstrated.

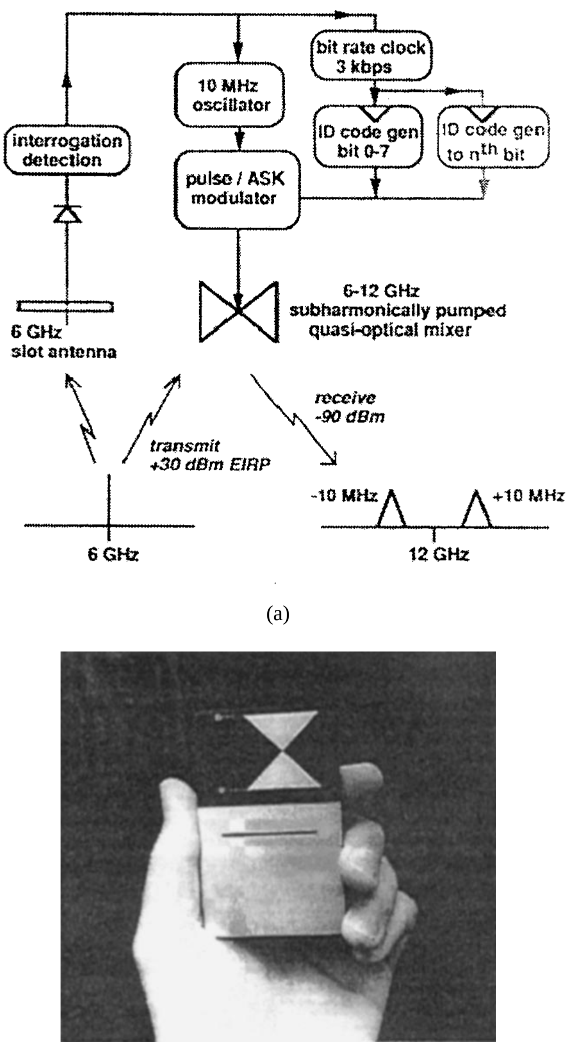


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Fig. 13. (a) Schematic diagram. (b) Photograph of a noncontact RF ID card [79].

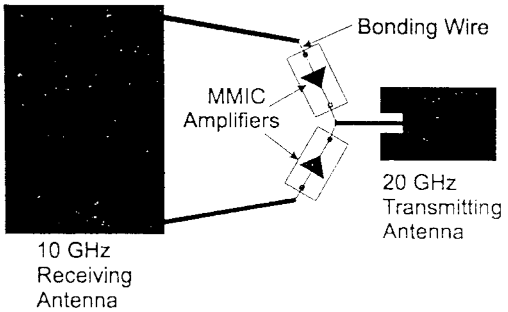

Fig. 14. A frequency-doubling integrated push–push active microstrip transponder [81].

As wireless applications move to higher frequencies, the AIA technique becomes an increasingly powerful alternative to conventional design approaches. Recently, an active silicon

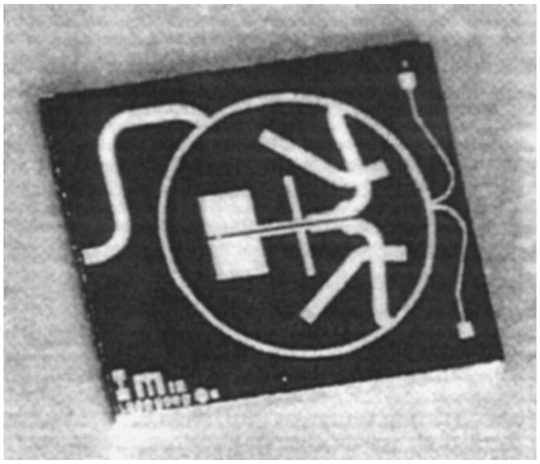

Fig. 15. A 76.5-GHz active SIMMWIC antenna for automotive applications [82].

monolithic millimeter-wave integrated-circuit (SIMMWIC) antenna for vehicular sensor application at 76.5 GHz was reported [82]. As shown in Fig. 15, this design features a patch antenna integrated with an IMPATT diode, as well as a traveling-wave rat-race coupler as the synchronizing network. The whole structure is monolithically integrated on 125-μm-thick high-resistivity silicon substrate, resulting in a very small chip size of 3.2×2.6 mm^2. This one-chip front-end achieves a high millimeter-wave output power up to 5 dBm, and highly decoupled ports for bias and subharmonic injection locking. With an injection power of 0 dBm at 25.5 GHz, a frequency-tuning range of 300 MHz was measured. Such novel AIA's are promising in realizing low-cost millimeter-wave sensor systems for automotive applications.

VIII. CONCLUDING REMARKS

As evidenced by the above examples, the AIA is a very useful concept in designing a great number of microwave and millimeter-wave application systems for both commercial and military purposes. We have tried to highlight some of the major areas of active research in this review. However, it should be pointed out that potential applications of the AIA will far exceed what we can describe or even predict here. With the steadfast progress in solid-state devices, integrated circuits, antennas as well as novel fabrication technologies such as microelectromechanical systems (MEMS), more innovative designs based on the AIA concept are expected to emerge in the coming years.

A final, but equally important, issue is the development of accurate and efficient computer-aided design (CAD) tools for AIA's. While many high-quality commercial packages are currently available for the analysis and design of complicated microwave and millimeter-wave circuits and various types of antennas, a unified full-wave simulation tool, which can take into account the tight circuit-antenna coupling effects within an AIA environment, remains an open challenge to the electromagnetics community. Fortunately, recent efforts to include nonlinear active devices into full-wave simulations based on transmission-line-matrix (TLM) [83], finite-difference time-domain (FDTD) [84]–[87], and finite-element time-domain (FETD) [88] techniques have shown impressive progress. Continued research activities in this direction should lead to the establishment of accurate and reliable analysis and design tools for AIA's in the foreseeable future.

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