INVITED PAPER

Leaky-Wave Antennas

The physics and operating principles of leaky-wave nonresonant antennas are summarized; recent developments of various configurations for scanning, surface conforming, and incorporation of active circuits are presented.

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ABSTRACT | This paper gives a basic review and a summary of recent developments for leaky-wave antennas (LWAs). An LWA uses a guiding structure that supports wave propagation along the length of the structure, with the wave radiating or "leaking" continuously along the structure. Such antennas may be uniform, quasi-uniform, or periodic. After reviewing the basic physics and operating principles, a summary of some recent advances for these types of structures is given. Recent advances include structures that can scan to endfire, structures that can scan through broadside, structures that are conformal to surfaces, and structures that incorporate power recycling or include active elements. Some of these novel structures are inspired by recent advances in the metamaterials area.

KEYWORDS | Antennas; broadside; endfire; leaky wave antennas; metamaterials; periodic structures; stopband

I. INTRODUCTION

Leaky-wave antennas (LWAs) have been in existence since the 1940s, when an LWA consisting of a slotted rectangular waveguide was introduced [1]. The field has been in steady development since then, with particular developments in more recent years being directed toward planar LWAs, which have the advantage of being low profile and easy to manufacture. The level of interest and the pace of development in the field of planar LWAs have recently accelerated significantly, partly due to the surge of interest in metamaterials. The purpose of this paper is to review the latest developments in the field of LWAs. Readers are referred to [2]–[6] for more background information and history.

A LWA, as defined here, is based on a guiding structure that is 1-D, meaning that the wave is guided in one direction along the guiding structure [5]. A typical example is a microstrip line that is periodically modulated in order to turn the nonradiating microstrip mode into a radiating leaky mode. This type of LWA radiates in a fashion similar to that of a linear array, creating either a fan beam at broadside or a conical beam that radiates at a scan angle θ_0 with respect to the axis of the guiding structure. The structure is typically fed at one end so that the wave propagates down the axis of the structure [as shown in Fig. 1(a)], although a center feed that creates a bidirectional excitation [as shown in Fig. 1(b)] is also possible and is sometimes very useful, especially for creating broadside beams. Two-dimensional LWAs that use a radially propagating leaky wave on a 2-D guiding surface have also been the subject of much interest recently, and the reader is referred to [2]–[4] for a discussion of these.

LWAs are popular in the microwave band and above, because they can achieve a high directivity with a simple structure, without the need for a complicated and costly feed network as typically used in a phased array. The pattern bandwidth (defined from the radiated power density at a fixed observation angle) is usually fairly narrow however, typically from about 1% to 10%. This is because the beam scans with frequency, with the pattern bandwidth decreasing as the beamwidth decreases. On the other hand, for applications that can take advantage of frequency beam scanning, LWAs are often ideally suited.

Recent developments include a LWA design that allows for improved endfire scanning. Also, much recent attention has been focused on overcoming the "open stopband" problem so that scanning from the backward region to the forward region through broadside is possible without suffering pattern degradation. Several designs for achieving this are reviewed. A design that allow for full-space scanning with lower permittivities than is usually possible

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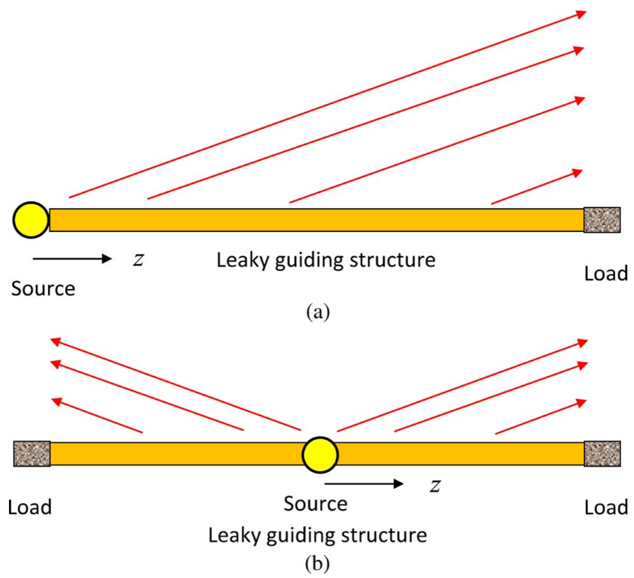

Fig. 1. *(a) Illustration of different modes of operation for an LWA. (a) Unidirectional case. (b) Bidirectional case.*

is also reviewed. Using bidirectional leaky waves to create broadside beams is also discussed. Other developments include the use of conformal LWAs for curved surfaces, power recycling to avoid wasting nonradiated power, and the inclusion of active elements into the LWA.

II. OVERVIEW OF LEAKY-WAVE ANTENNAS

A. Classification of LWAs

As stated above, a LWA is based on a guiding structure that propagates a wave in one direction, either unidirectionally (a source is placed at one end of the structure) or bidirectionally (a source is placed in the middle of the structure). One-dimensional LWAs can be broadly divided into two categories: *uniform* (or quasi-uniform) and *periodic*. A uniform LWA is one where the guiding structure is uniform along the length (taken here as the z-direction). In this case, the structure supports a wave that is fast with respect to free space, so that the complex wavenumber of the leaky mode $k_z = \beta - j\alpha$ has a phase constant in the range $0 < \beta < k_0$. A *quasi-uniform* LWA operates in a similar fashion as does a uniform one, except that a periodic structure is used to guide the wave. The periodicity, which is usually much less than a wavelength, plays no direct role in the radiation, however.

A periodic LWA is one where the guiding structure supports a wave that is slow with respect to free space, so that $\beta > k_0$. The fundamental nonradiating mode is made to radiate by introducing periodicity along the length of the structure. The field on the structure is then characterized by an infinite number of space harmonics (also called Floquet waves) having wavenumbers [7]

$$k_{z,n} = k_{z,0} + \frac{2\pi n}{p} \tag{1}$$

where p is the period in the z-direction. One of the advantages of a periodic LWA is that a beam can be created in either the forward or backward directions, since $\beta_{-1} = \mathrm{Re}(k_{z,-1})$ can be either positive or negative.

In addition to the two main types of guiding structures (uniform or quasi-uniform versus periodic) there are also two ways in which an LWA can be fed: from one end of the structure, or from the center of the structure.

B. Modes of Operation and Basic Principles

There are four possible operational configurations for 1-D LWAs, since the structures can be either uniform/quasi-uniform or periodic, and they can be fed either at one end of the structure (unidirectional leaky wave) or in the middle of the structure lengthwise (bidirectional leaky wave). Different types of beams can be obtained depending on the case. Each case in summarized below.

1) Uniform/Quasi-Uniform Unidirectional: The structure is fed at one end ($z = 0$) and typically an absorber or matched load is placed at the other end ($z = L$) to absorb residual power, as shown in Fig. 1(a). Along the structure the radiating field or current has the form

$$\psi(z) = Ae^{-jk_z z} \tag{2}$$

where $k_z = \beta - j\alpha$. In most cases, $\beta > 0$ (the wave is a forward wave with a positive phase velocity), though backward-wave structures with $\beta < 0$ are also possible, as discussed later. The radiation efficiency due to the load absorption is $e_r = 1 - \exp(-2\alpha L)$. A typical choice for the efficiency is around $e_r = 0.9$ (i.e., 90%), which maximizes the overall gain for a given antenna length L [8].

The structure radiates a conical beam at an angle θ_0 from the z-axis, where $\beta = k_0 \cos\theta_0$. The cone of radiation is in the forward direction ($0^\circ < \theta_0 < 90^\circ$) for $\beta > 0$ and in the backward direction ($90^\circ < \theta_0 < 180^\circ$) for $\beta < 0$. When the structure supports only a forward wave, the antenna cannot radiate exactly at broadside, since we always have $\beta > k_0$. If the structure supports either a forward or a backward wave, it may be able to radiate at broadside [as with the composite right/left-handed (CRLH) structure discussed later]. In this case, a fan beam is produced at broadside. The antenna may be able to radiate at endfire ($\theta_0 = 0^\circ$) or backward endfire ($\theta_0 = 180^\circ$), but this depends on the element pattern of the radiating source. If the element pattern has a null at endfire or backward endfire, then the LWA cannot radiate in these directions. If the structure can radiate at endfire or backward endfire, the beam will change from a conical beam to a pencil beam as forward/backward endfire is approached.

2) Uniform/Quasi-Uniform Bidirectional: The structure is fed in the middle ($z = 0$) and typically an absorber or matched load is placed at the other two ends ($z = \pm L/2$) to absorb residual power, as shown in Fig. 1(b). The feed is chosen to excite the radiating field or current symmetrically. Along the structure the radiating field or current then has the form

$$\psi(z) = Ae^{-jk_z|z|}. \tag{3}$$

The structure radiates a pair of conical beams pointing at $\theta = \pm\theta_0$. For the infinite aperture case (i.e., $L \to \infty$) the location of the beam maximum for $\beta > \alpha$ is [9]

$$\cos^2\theta_0 = (\beta/k_0)^2 - (\alpha/k_0)^2. \tag{4}$$

The two conical beams will merge into a single fan beam pointing at broadside ($\theta_0 = 90^\circ$) whenever $\beta < \alpha$. For those structures based on a rectangular or parallel-plate waveguide, the maximum power density radiated at broadside by a simple dipole source inside the structure will occur when $\beta = \alpha$, while the narrowest fan beam will occur when $\beta = 0.518\ \alpha$ [9]. An array of 1-D LWAs can be used to create a pencil beam at broadside, in which case the same optimum condition applies.

3) Periodic Unidirectional: In this case, a periodic LWA is fed at one end ($z = 0$) and a load is placed at the other end ($z = L$). The fundamental mode is a slow wave, but radiation occurs from the $n = -1$ space harmonic, which may be forward ($\beta_{-1} > 0$) or backward ($\beta_{-1} < 0$). Hence, the LWA can be used to create a beam pointing in either the forward direction ($0 < \theta_{-1} < 90^\circ$) or the backward direction ($90^\circ < \theta_{-1} < 180^\circ$). The beam angle will increase as the frequency increases, and hence this type of LWA is often used to scan the beam with frequency. In order to scan the beam from backward endfire to forward endfire in single-beam operation, so that only the $n = -1$ space harmonic radiates, the effective permittivity of the guiding structure (assuming a quasi-TEM guiding structure) must be chosen so that $\varepsilon_r^{\mathrm{eff}} > 9$ [4]. This is equivalent to the condition that $\beta_0/k_0 > 3$.

From (1), we have $\beta_0 p = 2\pi$ at broadside, corresponding to a stopband of the periodic structure, which for a radiating LWA is called the "open stopband at broadside" [3], [4]. Most periodic LWAs cannot radiate well exactly at broadside. Typically, the LWA, which normally supports a traveling wave, turns into a standing-wave type of antenna at this frequency, where all of the radiating elements in the different unit cells are excited equally. (This is equivalent to saying that the attenuation constant drops to zero.) Although broadside operation as a standing-wave antenna at one fixed frequency is certainly possible and is easy to obtain, the characteristics will be quite different from that of the same structure when operating as a LWA at a scan angle different from broadside. In particular, the beamwidth and input impedance will be very different, so that the antenna characteristics will change drastically as the antenna scans with frequency through broadside (and more so as the length of the structure increases). This results in a serious degradation of the scan performance near broadside. Novel structures have recently been proposed to overcome this limitation, and these are discussed later.

A periodic LWA that has only pure series or shunt radiating elements cannot overcome the stopband problem (at the stopband frequency $\beta_0 p = 2\pi$, and hence the impedance seen at the elements will always be an open or short circuit, respectively). The novel structures thus have unit cells that are more complicated than simple series or shunt elements.

4) Periodic Bidirectional: In this category, the periodic LWA is fed in the center to create a bidirectional leaky wave, just as for the uniform case (case 2) above. As mentioned above for the periodic unidirectional case, if the frequency of operation is selected exactly at the stopband so that $\beta_{-1} = 0$, the structure becomes a standing-wave antenna (now fed in the center instead of at the end), which can radiate at broadside, but no longer acts as a leaky-wave (traveling-wave) structure. The structure can, however, radiate at broadside as a LWA by operating slightly away from the broadside frequency, so that $\beta_{-1} > 0$ or $\beta_{-1} < 0$. In this case, a bidirectional beam is created in which the beam from each half of the structure is pointed slightly off of broadside, but the combination of the two beams results in a symmetrical broadside beam. For many structures, the LWA can be modeled as a transmission line with a periodic set of series or shunt loads. In this case, it has been shown that the maximum power density radiated at broadside occurs when $|\beta_{-1}| = \alpha$ [10]. In particular, $\beta_{-1} = \alpha$ holds at the optimum frequency for series capacitive loads or shunt inductive loads, and the optimum frequency is above the stopband frequency; $\beta_{-1} = -\alpha$ holds at the optimum frequency for series inductive loads or shunt capacitive loads, and the optimum frequency is below the stopband frequency [10].

III. RECENT DEVELOPMENTS IN LEAKY-WAVE ANTENNAS

In this section, some recent developments in 1-D LWAs are overviewed. Due to space limitations, only the most relevant properties are summarized, and the reader is referred to references for more details. No attempt is made to cover every recent development, but a representative sample is chosen.

1) Endfire Substrate Integrated Waveguide (SIW) LWA: LWAs usually cannot scan all the way down to endfire, since the radiating elements (slots, stubs, etc.) have an element pattern that prohibits this. The SIW LWA shown in Fig. 2(a) is one recent structure that can produce a pencil beam at endfire. It consists of an SIW waveguide with a periodic array of transverse slots [11]. The SIW waveguide operates in the TE_{10} mode, and hence the SIW waveguide simply acts as an equivalent rectangular waveguide, made in integrated form. Leakage occurs through the slots, the dimensions of which control the leakage rate (attenuation constant due to leakage). The slots are fairly closely spaced, so the structure is a quasi-uniform LWA, radiating from the slot-perturbed TE_{10} mode that is a fast wave. The beam radiated would normally be a conical beam, but as discussed in Section II-B1, the beam becomes a pencil beam at endfire ($\theta_0 = 0$) if the element pattern allows for endfire radiation. This is the case here, since the slot fields are equivalent to magnetic currents in the x-direction.

Fig. 2(b) shows the fabricated structure, in which there is a taper in the slot dimensions at both ends. An output microstrip line is terminated with a load to absorb residual power. In Fig. 2(c), the theoretical and measured patterns are shown at a frequency of 11.7 GHz. At this frequency, the theoretical beam (for an infinite ground plane) has not quite reached endfire yet, and the pattern is down by about 6 dB at endfire relative to the peak of the beam, which occurs at about 20°. The structure is also simulated using the commercial tool Ansys high frequency structure simulator (HFSS). The HFSS result for the infinite ground plane shows less than a 2-dB drop at endfire relative to the beam peak. For the finite ground plane the measurement shows a drop of about 6 dB at endfire relative to the beam peak, while the HFSS simulation shows a drop of about 10 dB.

Fig. 2(d) shows the E-plane pattern at 12 GHz, where the leaky mode is now at endfire with $\beta = k_0$. Note that the theoretical pattern (which assumes an infinite ground plane) and the numerically simulated pattern from HFSS agree well and predict an endfire beam at this frequency, assuming an infinite ground plane is used in the HFSS simulation. However, when a finite-size ground plane is used, the simulation shows a gain loss of about 6 dB at endfire relative to the beam peak, as seen in Fig. 2(d). This is consistent with edge diffraction theory (GTD), since GTD predicts a field level that is down by a factor of 1/2 at the shadow boundary (i.e., $\theta = 0°$). As the size of the ground plane increases, the pattern should approach that of the infinite ground plane case for all angles not equal to 90°, but exactly at endfire the pattern will always exhibit the 6-dB drop due to diffraction. The closer the observation angle is to 90°, the larger the ground plane would have to be in order for the pattern of the finite ground plane to match well with the pattern of the infinite ground plane. Exactly at 90° they will never match, and will differ by 6 dB.

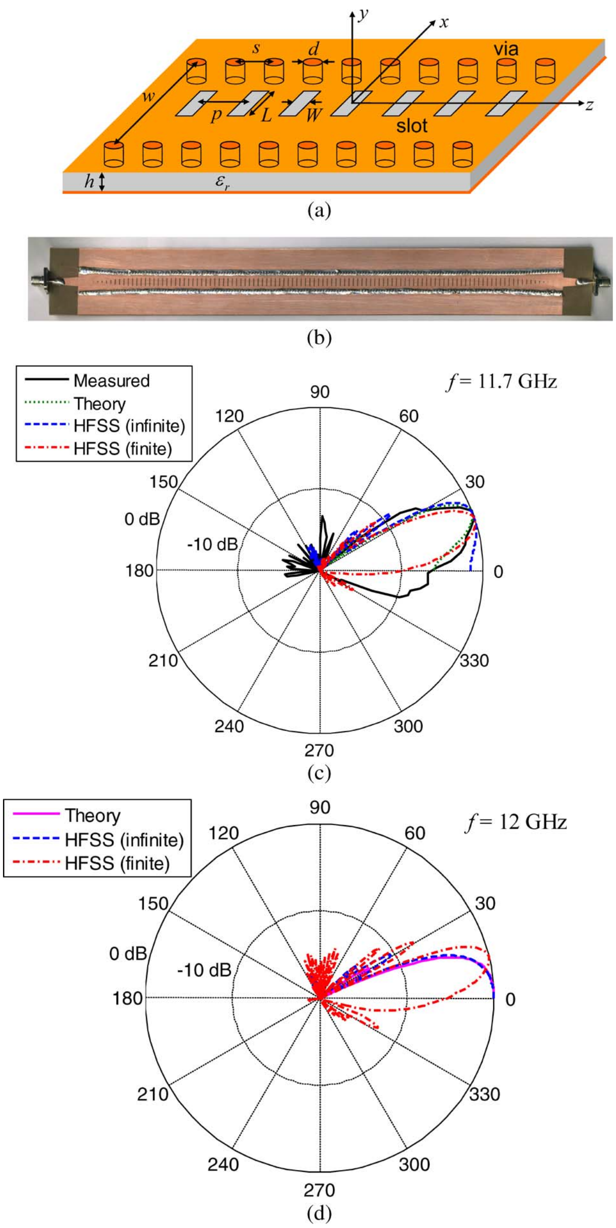

Fig. 2. ***SIW LWA. (a) Geometry of the structure. (b) Fabricated structure. (c) Measured (finite ground plane) and theoretical (infinite ground plane) E-plane patterns of the structure at 11.7 GHz. Also included are results from HFSS for both finite and infinite ground planes. (d) Simulated E-plane patterns of the structure at 12 GHz. The theoretical pattern (infinite ground plane) is shown along with patterns from HFSS for both finite and infinite ground planes. The length and the width of the ground plane are 310.2 and 40 mm, respectively.***

The directivity is maximized at a slightly higher frequency of about 12.2 GHz (not shown). At this frequency, $\beta \approx 1.05\ k_0$. This is consistent with the Hansen–Woodyard condition for maximizing endfire directivity [8], which

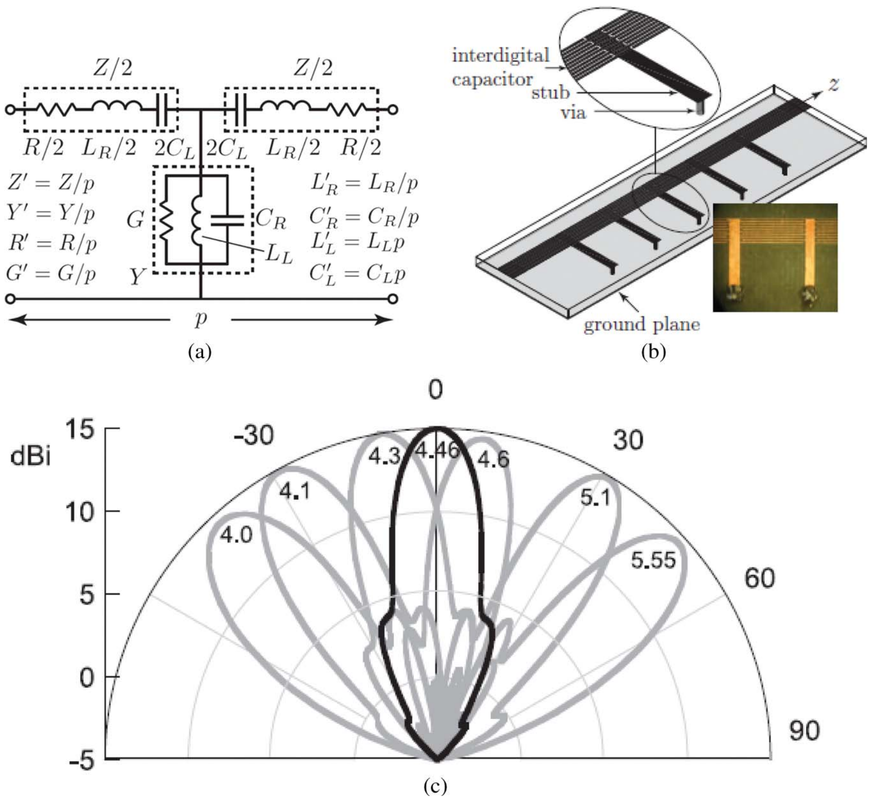

Fig. 3. ***CRLH LWA. (a) Unit cell of the CRLH structure. (b) Practical realization of the CRLH structure. (c) The beam from the CRLH LWA is shown scanning through broadside by changing frequency for one particular structure (frequencies in gigahertz are labeled).***

predicts that the optimum phase constant is approximately $\beta = k_0 + 2.94/L$. (This equation for the optimum phase constant holds for the case when $\alpha = 0$, but the optimum phase constant for $\alpha > 0$ is usually not too different [8].)

2) CRLH LWA: The CRLH LWA led to a breakthrough in LWA design, since it was the first such structure that was able to successfully scan through broadside without beam degradation [12]. As noted in Section II-B3, an open stopband at broadside usually prohibits broadside radiation from a unidirectional periodic LWA. Indeed, the open stopband will always occur when the periodic structure consists of only series or shunt radiating elements, such as a microstrip line loaded periodically with stubs, etc. The CRLH structure is a metamaterial-inspired design that consists of a periodic arrangement of inductor and capacitor elements within a transmission line unit cell, as shown in Fig. 3(a). The "right-handed" elements are those that would normally be present in the unit cell of a small length of transmission line. The "left-handed" elements are those that have been artificially added. The resistances account for material loss as well as radiation. The structure is classified as quasi-uniform, since the period is small relative to a wavelength, and hence the structure radiates from the fundamental $n = 0$ space harmonic. If the period is small relative to a wavelength, the structure can be modeled fairly accurately as a uniform artificial transmission line, with the unit cell shown in Fig. 3(a). The addition of the left-handed elements allows the transmission line (TEM) mode to have either a positive or negative phase constant. The phase constant will be negative (i.e., a backward wave, assuming that the power flow is in the positive z-direction) when $\omega < \min(\omega_{se}, \omega_{sh})$, where ω_{se} and ω_{sh} are the resonance frequencies of the series and shunt branches, given by

$$\omega_{se} = \frac{1}{\sqrt{L_R C_L}} \quad \omega_{sh} = \frac{1}{\sqrt{C_R L_L}}. \tag{5}$$

The phase constant will be positive when $\omega > \max(\omega_{se}, \omega_{sh})$. In the frequency region $\min(\omega_{se}, \omega_{sh}) < \omega < \max(\omega_{se}, \omega_{sh})$, there will be a stopband (the wave number of the transmission line mode will be imaginary). The stopband is eliminated when the structure is "balanced" so that $\omega_{se} = \omega_{sh}$. In this case, the frequency $\omega_0 = \omega_{se} = \omega_{sh}$ is the broadside frequency.

It is interesting to note that at the broadside frequency, the attenuation constant can be shown to be equal to [13], [14]

$$\alpha = \sqrt{R'G'} \tag{6}$$

where R' and G' are the per-unit-length series resistance and shunt conductance. Hence, in order to have a nonzero value of α at the broadside frequency (and hence an elimination of the stopband), it is necessary to have a unit cell with both R and G present, a property that occurs naturally with the CRLH structure. This means that in a lossless structure, radiation cannot occur from only the series element or the shunt element, but must come from both. Furthermore, it has been shown that in order to have good radiation efficiency at broadside, significant radiation must come from both the series and shunt elements, and not just one of them [15].

Fig. 3(b) shows a realization using short-circuit stubs to realize the left-handed (i.e., shunt) inductors and interdigital capacitors to realize the left-handed (i.e., series) capacitors. Fig. 3(c) shows the radiation pattern scanning though broadside as the frequency increases for a typical structure, with the beam shape staying almost constant.

The CRLH principle is not limited to planar microstrip-based structures, but has also been extended to waveguides [16], [17]. In this case, a rectangular waveguide is used that has a periodic set of transverse slots on the broad wall that are backed by short-circuited sections of waveguide, which make the slots capacitive in nature. When operating below the cutoff frequency of the main waveguide, the main waveguide has a transmission line model that has a series inductance and a shunt inductance in a differential unit cell section, for the TE_{10} mode. With the series capacitance added from the slots, the unit cell model then becomes one with an overall series capacitance and a shunt inductance. Hence, a left-handed propagation behavior is obtained. Above the cutoff frequency of the main waveguide, a right-handed behavior is obtained, assuming that the series inductance dominates over the series capacitance. By proper optimization, a balanced design can be achieved in which the left-handed mode transitions smoothly to the right-handed mode without a bandgap, meaning continuous scanning from the backward quadrant to the forward quadrant, just as with the CRLH planar antenna.

3) Quarter-Wave Transformer LWA: After the CRLH structure was conceived [18], it was realized that "conventional" periodic LWAs that radiate from the $n = -1$ space harmonic could also be constructed that can scan through broadside. One design that was proposed is the "quarter-wave transformer" design, in which a quarter-wave matching transformer is incorporated into the unit cell of a periodic LWA [19]. The method is quite general, and can be used with any periodic LWA. To illustrate the principle, consider starting with a "combline" LWA that consists of a microstrip line periodically loaded with radiating stubs. By adding a matching transformer within the unit cell, we arrive at the structure shown in Fig. 4(a). Assume hypothetically for the moment that at the broadside frequency the input impedance on the microstrip line seen looking to the right, just to the right of a radiating stub, is equal to the microstrip line impedance Z_0. Just to the left of the stub the input impedance will be Z_0 in parallel with the stub impedance. The parallel combination is denoted as Z_L. We can then find a distance d along the line from the stub for which the input impedance will be purely real. The input impedance at this point is denoted as R_d. We then place a quarter-wave matching transformer with characteristic impedance Z_T at this location to transform this real input impedance R_d to the value Z_0 by using $Z_T = \sqrt{Z_0 R_d}$. The input impedance looking to the right will then be Z_0 at any point on the microstrip line to the left of the transformer, until we reach the next stub. The input impedance looking to the right at the point just to the right of this next stub is thus Z_0. This was our starting assumption, and hence the solution for the periodic structure is self-consistent and therefore correct.

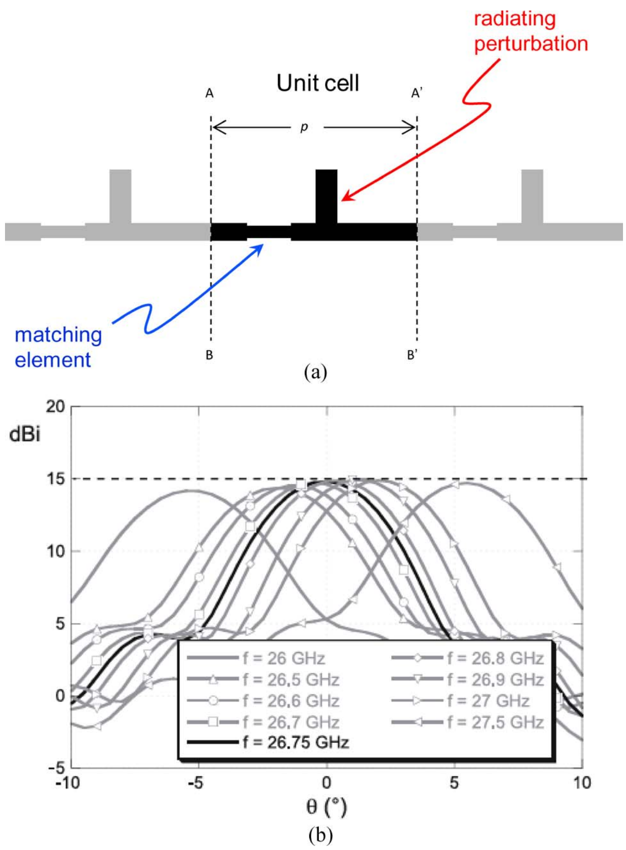

Fig. 4. ***Quarter-wave transformer LWA. (a) Geometry of the structure. (b) The beam from the structure is shown scanning through broadside by changing frequency for one particular structure.***

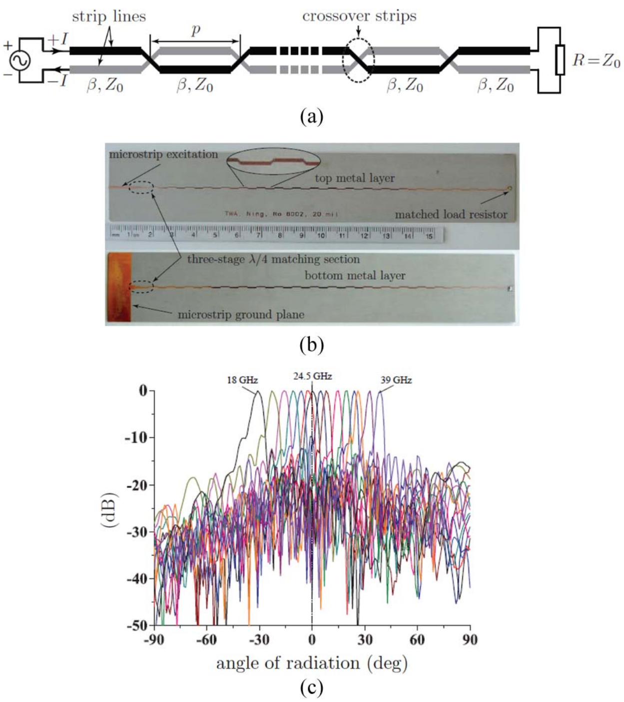

Fig. 5. ***Phase-reversal LWA. (a) Geometry of the structure. (b) Fabricated structure. (c) The beam from the structure is shown scanning through broadside by changing frequency.***

Fig. 4(b) shows results from one particular design, and it is seen that the beam shape is preserved as the beam scans through broadside, just as it is with the CRLH structure.

4) Phase-Reversal LWA: This structure presents a modification of a periodic LWA that allows for the beam to scan from backward to forward endfire using a lower permittivity than would normally be possible [20]. (The usual requirement is $\varepsilon_r^{\rm eff} > 9$, as discussed in Section II-B3.) The structure is shown in Fig. 5(a). The structure consists of two parallel microstrip lines printed on opposite sides of the substrate board, which periodically cross each other. The microstrip lines form an "offset parallel strip" (OPS) transmission line. The region where the lines cross is the discontinuity from which radiation occurs, although in a more general situation, other radiating elements could be added within the unit cell as well.

The crossovers act to introduce a 180° phase shift in the mode on the OPS transmission line. (Introducing a 180° phase shift within the unit cell has been done with other periodic structures in the past [7], though evidently not with printed LWA structures such as this one.) This phase shift causes the dispersion curves in the Brillouin diagram (a plot of $k_0 p$ versus βp) to shift by π. This shift allows the $n = -1$ space harmonic to reach forward

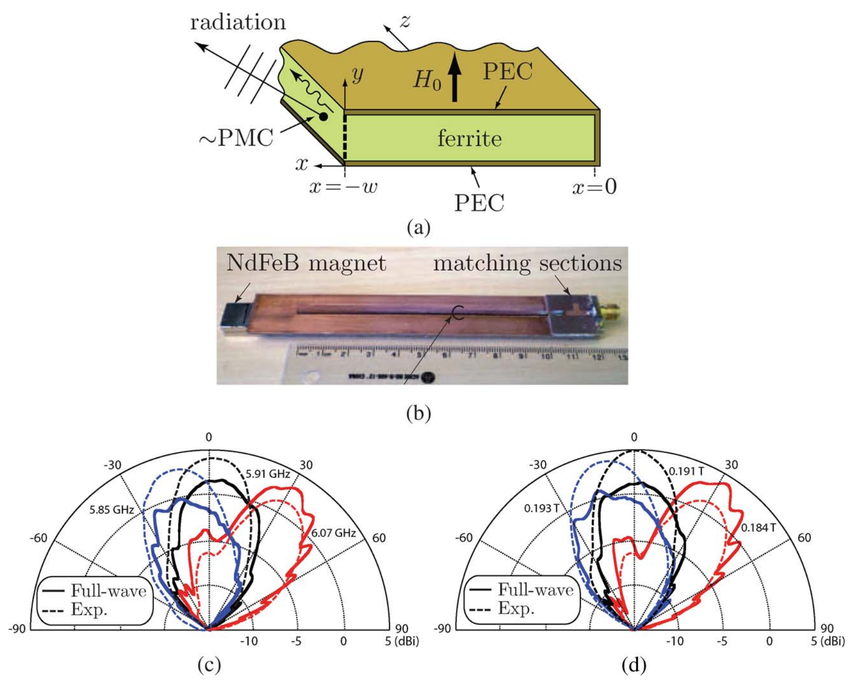

Fig. 6. ***Ferrite LWA. (a) Geometry of the structure. (b) Fabricated structure. (c) The beam from the structure is shown scanning through broadside by changing frequency. (d) The beam from the structure is shown scanning through broadside via electronic control, by changing the biasing magnetic field (in Tesla) of the ferrite.***

endfire at a considerably lower frequency than for a usual periodic LWA. The result of this is that single beam operation from backward endfire to forward endfire is possible using only $\varepsilon_r^{\text{eff}} > 4$. By a careful design of the radiating crossover, which can be modeled as a T network, it is also possible to eliminate the open stopband. This is done by using the T circuit as a matching transformer, similar in spirit to the quarter-wave transformer design discussed above.

Fig. 5(b) shows the fabricated prototype. Fig. 5(c) shows the beam scanning with frequency. The beam is shown scanning over the region $(-30°, 45°)$, though in principle a full-space scanning should be possible. (The scan range was limited here by the experimental setup, not the antenna.) Note that the beam scans through broadside with no degradation.

5) Ferrite LWA: It was mentioned in Section II-B1 that a uniform LWA that can produce a beam in the backward direction (having $\beta < 0$) requires a more exotic material than simply metallic and dielectric structures. One interesting uniform LWA that has been developed having this backward-wave property is a LWA using a ferrite material. The LWA consists of a rectangular waveguide having an open side face through which radiation occurs, as shown in Fig. 6(a) [21]. The waveguide is filled with a ferrite material that is biased in the direction perpendicular to the top face of the waveguide (the y-direction in the figure). The structure operates in a field configuration similar to that of the rectangular waveguide TE_{10} mode (no vertical variation of the fields) when the height is much smaller than the width. When the ferrite is biased, multiple modes are found to exist, depending on the frequency region. In one frequency band, the mode is similar to the mode on the CRLH LWA, in that the mode transitions from a backward wave to a forward wave as the frequency increases. Furthermore, this mode does not exhibit a stopband at broadside ($\beta = 0$), since it is not a periodic structure. Hence, the behavior is similar to that of the balanced CRLH structure. Fig. 6(b) shows the fabricated structure. Fig. 6(c) shows simulated and measured patterns as the frequency changes, verifying that the beam can scan through broadside without degradation. Fig. 6(d) shows that electronic scanning through broadside is also possible by varying the bias on the ferrite.

6) Bidirectional LWAs: As discussed in Section II-B2, a uniform or quasi-uniform LWA fed in the center can be used to create a bidirectional leaky wave and thus create a beam at broadside. The LWA may consist of a linear 3-D structure (microstrip line, waveguide, etc.) or a 2-D structure where the field is invariant in one direction (e.g., a parallel-plate waveguide). In the latter case, a line-source type of excitation (invariant in one direction) is needed, and a pencil beam is created by taking the width of the structure (in the direction of the line source) sufficiently large.

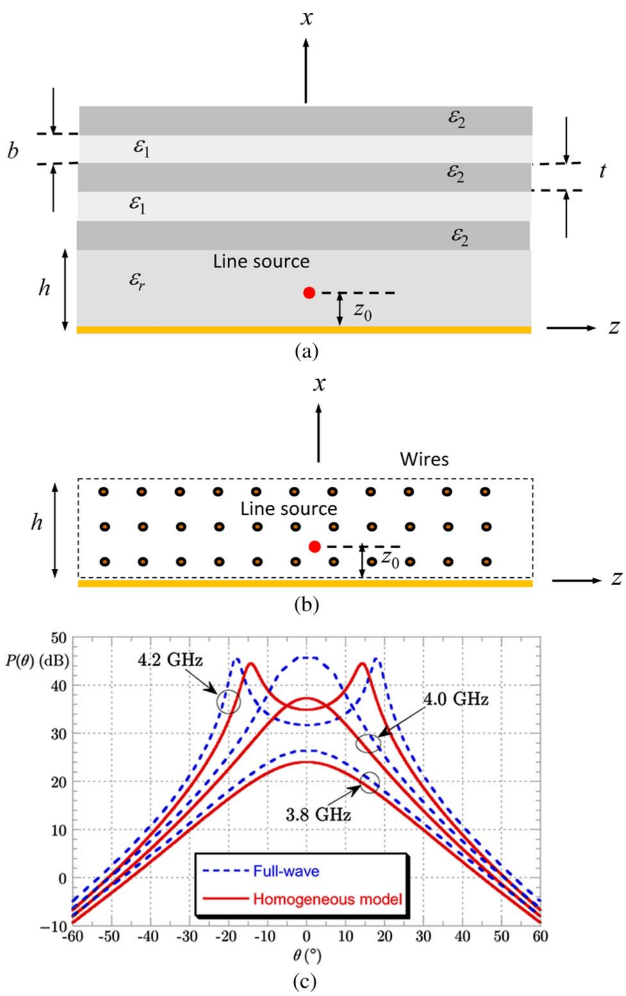

Fig. 7. ***Bidirectional LWAs. (a) A stack of alternating low/high permittivity dielectric layers above a substrate is used to create a parallel-plate waveguide region. The structure is excited bidirectionally with a line source in the center. (b) An artificial slab of low permittivity realized by a periodic arrangement of metallic wires is used to create a parallel-plate waveguide region. The structure is excited bidirectionally with a line source in the center. (c) Radiation patterns for the structure of Fig. 7(b), showing how a broadside beam is obtained at the optimum frequency (4.0 GHz).***

Fig. 7(a) shows one type of structure, consisting of an "electromagnetic band gap (EBG)" structure forming the top of a parallel-plate waveguide that is filled with a substrate material. The EBG consists of an alternating stack of low and high permittivity dielectric layers with $\varepsilon_2 > \varepsilon_1$ [22]. The thickness of the parallel-plate waveguide is one-half of a wavelength in the substrate dielectric. The EBG structure acts as a high reflectance surface for waves inside the parallel-plate region impinging normally on the EBG when the EBG layers are each one-quarter of a wavelength thick in the respective dielectrics.

Fig. 7(b) shows another type of structure, where an artificial low-permittivity grounded substrate layer is realized by using a wire medium [23]. It is now the contrast in permittivity between the low-permittivity substrate and the surrounding air that causes a high reflectance and creates the leaky wave. The structure is optimized when the thickness of the low-permittivity substrate is one-half of a wavelength in the low-permittivity dielectric. At this frequency, $\beta \approx \alpha$ for the leaky wave. Fig. 7(c) shows the beam from this structure at several frequencies, showing that at the optimum frequency of 4.0 GHz a directive broadside beam is created. It is also seen that using a homogenized substrate approximation agrees well with the full-wave simulation, which accounts for the actual wires.

Although not discussed in this paper, the Fabry–Pérot resonant cavity antenna is a 2-D version of the bidirectional LWA, in which a radially propagating leaky wave is excited on a planar guiding structure. An example of such a structure would be the stacked dielectric structure of Fig. 7(a) with the line source replaced by a horizontal dipole source. Such a structure can radiate either a conical beam or a pencil beam at broadside. More details on the operation of this type of structure may be found in [2]–[4].

7) Conformal LWA: This is more of a novel application of a LWA than a particular type of LWA. In this application, a LWA is put on a curved surface such as a cylinder. The cylinder can be round or of any shape. A three-faced cylinder is shown in Fig. 8(a) [24]. The goal is to radiate a narrow beam in a fixed direction. Because of the curvature of the cylinder, the LWA should radiate a beam locally at an angle (with respect to the propagation direction of the leaky wave) that changes as the position on the cylinder

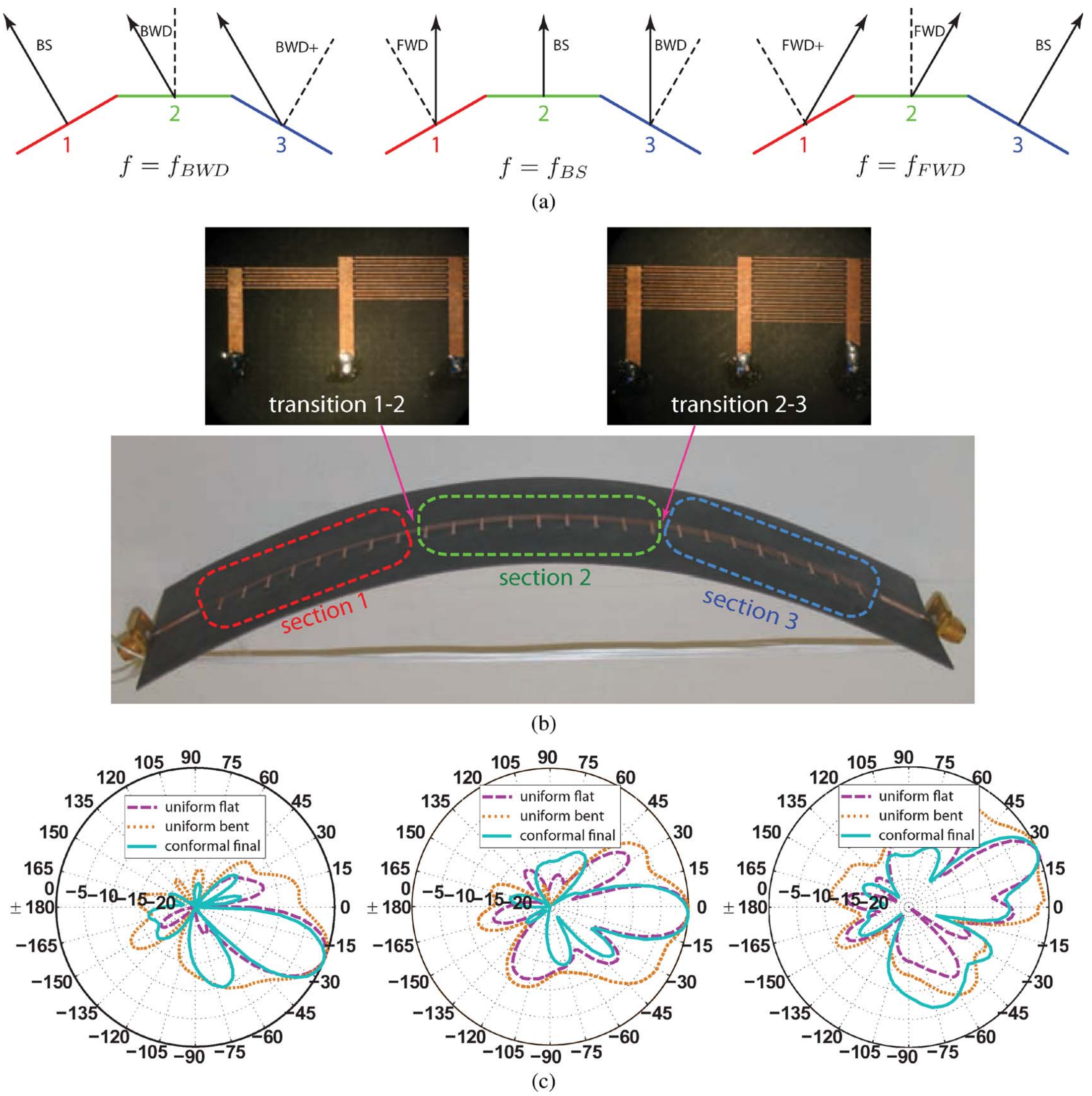

Fig. 8. ***Conformal LWA. (a) Sketch of the radiating beam for a LWA on a three-sided cylindrical surface. (b) A fabricated CRLH prototype, made from three sections. (c) Radiation patterns for the conformal CRLH LWA, compared with patterns for a conventional (designated as "uniform" in the figure) CRLH structure, either on a flat surface or bent and mounted on the cylindrical surface.***

changes. In this way, the radiation from all points on the LWA is focused in the same direction. Notice that the radiated beam is pointing locally in the backward direction for some points on the cylinder, in the forward direction for other points on the cylinder, and at broadside for one point on the cylinder. This is illustrated in Fig. 8(a). Because the local angle of radiation needs to change with position, and broadside is included, this application requires a LWA that can radiate in both directions and at broadside as well.

One candidate LWA that has been explored for this application is the CRLH LWA. Fig. 8(b) shows a CRLH LWA on a thin substrate, which is then conformally mounted on a three-faced cylindrical surface. The LWA was composed of three sections, each with a different local beam angle. Fig. 8(c) shows a comparison of patterns. One pattern is that of the conformal LWA radiating on the three-faced cylindrical surface. The other patterns are that of a "regular" CRLH LWA designed to radiate at broadside on a flat surface, which is then either kept flat or bent and mounted on the cylindrical surface. Notice that the curved surface seriously degrades the pattern of the regular CRLH antenna, but the conformal CRLH antenna has a pattern that is close to that of the regular CRLH radiating from a flat surface. Hence, the compensation for the curved surface in the conformal design is nearly ideal.

8) Power Recycling LWA: Normally, a LWA is terminated with a load at the end to avoid reflections. However, it has recently been demonstrated that as an alternative to this, the power left over at the end of the LWA can be "recycled" back into the LWA, thereby increasing the overall efficiency of the system. The design is shown in Fig. 9(a) [25]. A rat-race coupler is used to connect the input and output ports of the LWA. Power from the source goes into port 1 of the coupler and emerges from port 4 to go into the input port of the LWA (port 5). Remaining (nonradiated) power from the output port of the LWA (port 6) goes into port 3 of the coupler and emerges from port 4, where it is fed back into the input port (port 5) of the LWA. At the design frequency for which the coupler is designed, no power emerges from the load port on the coupler (port 2). At other frequencies (if the antenna is frequency scanned, for example) there will be some amount of power that is absorbed in the load, depending on the frequency. Fig. 9(b) shows an implementation of the power-recycled LWA, using a CRLH antenna (though any other LWA could be used), designed for broadside operation at 4.58 GHz. The measured radiation efficiency of the CRLH LWA by itself without the power recycling was measured as 38% for this particular design. With the power recycling, the efficiency increased to 68%. These numbers will, of course, depend on the specific LWA chosen, but they demonstrate that an improvement in efficiency is possible, which may be significant if the original LWA has a low efficiency.

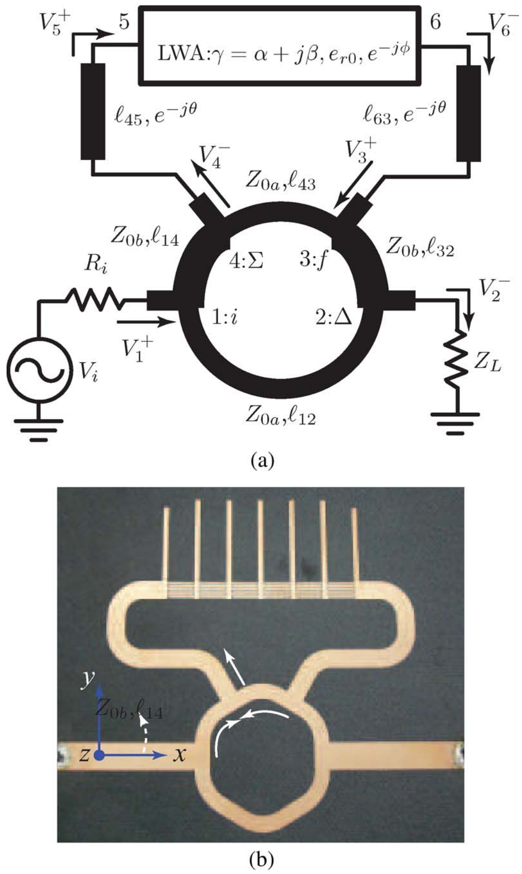

Fig. 9. ***Power-recycling LWA. (a) Schematic of the power-recycling scheme. (b) Fabricated structure using the CRLH LWA.***

9) Active LWA: Field effect transistors (FETs) have been incorporated into an amplifier design that uses two microstrip lines, a "drain line" and a "gate line," connected to the drain and gate terminals of the FETs, respectively, as shown in Fig. 10(a) [26]. This configuration, by itself would normally be used as a (nonradiating) broadband distributed amplifier (DA). Either the drain line or the gate line, or both, can be made into LWAs, which allows for various functionalities, depending on the configuration, giving rise to a DA-LWA [27]. Fig. 10(b) (left side) shows the drain line replaced with an LWA, using the CRLH structure (though other types of LWAs could be used). This configuration allows the signal from the source on the gate line to get amplified and radiated by the LWA that is used as the drain line. Fig. 10(b) (right side) shows the gate line replaced with the LWA. In this case, an incoming signal that impinges on the gate line (LWA) gets amplified and sent to a receiver on the drain line, which may be placed at either the right or left end of the drain line, depending on whether the gate line LWA is operating in forward-wave or backward-wave mode. If both the gate and drain lines are replaced by LWAs, the structure can act as a transponder, amplifying and reradiating an incoming signal. Fig. 10(c)

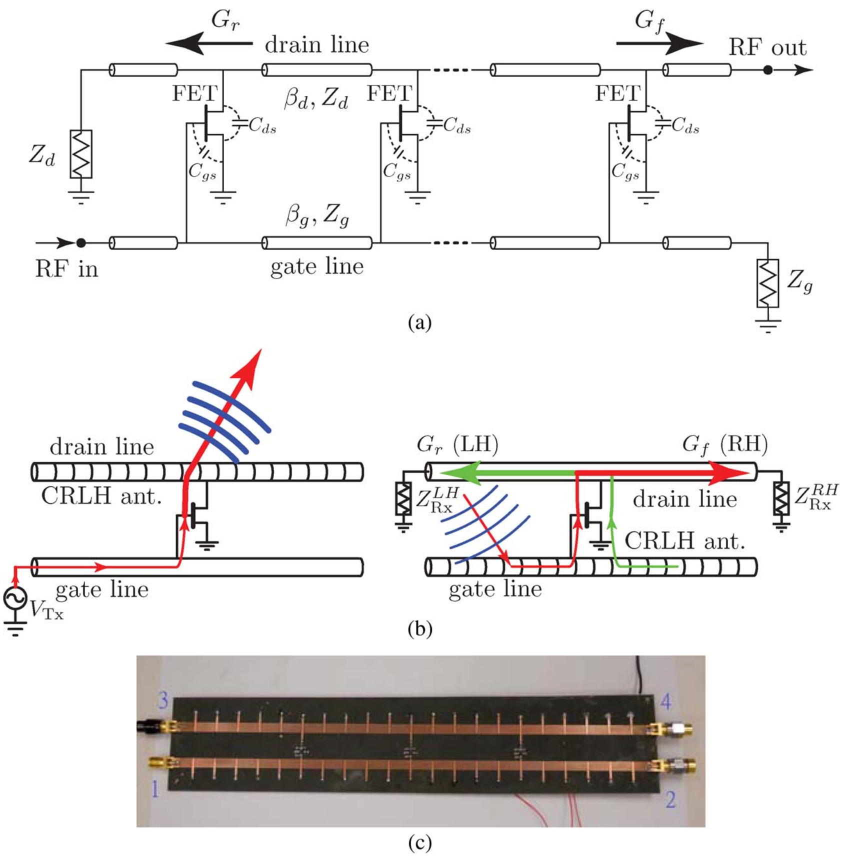

Fig. 10. *Active LWA. (a) Schematic of the active distributed amplifier structure. (b) The drain line is replaced by a CRLH LWA (left) and the gate line is replaced by a CRLH LWA (right). (c) A fabricated structure using CRLH LWAs to replace both the drain and gate lines.*

shows a fabricated DA-LWA using CRLH LWAs for the drain and gate lines. Recently, the DA LWA has also been combined with a power-recycling rat race as described in Section III-8 [28]. This antenna not only amplifies the signal, but also recycles the nonradiated power as well.

IV. CONCLUSION

This paper has summarized some of the recent developments in the field of LWAs. Although LWAs have been in existence since the 1940s, the field has seen significant developments in recent years, with much of the recent work being in the area of planar LWAs, which are low profile and relatively easy to manufacture. Some of the recent developments in the LWA field have been related to the recent developments in the metamaterials area, which has provided new inspiration for novel designs. Various designs that overcome the stopband problem at broadside and allow for continuous beam scanning through broadside have been reviewed. Other developments that have been reviewed include LWAs that can scan to endfire, that can be mounted conformally on a curved surface, and that have power-recycling capability. Active LWAs incorporating amplifiers were also reviewed. ■

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