Planar Leaky-Wave Antennas – Early Concepts and Actual Results

Wolfgang Menzel
Institute of Microwave Techniques
University of Ulm, D-89069 Ulm, Germany
wolfgang.menzel@uni-ulm.de

***Abstract*—Leaky-wave antennas are based on the radiation along transmission lines, either due to natural radiation regimes or periodic perturbations. The leaky nature of *higher-order modes of microstrip lines* was a discovery only at the end of the 1970's. Phase (velocity) engineering by metamaterial used for leaky-wave antennas came up in the early 2000's. This overview gives a short review of basics and three examples of realized leaky-wave antennas.**

Keywords—antennas, leaky-wave antennas, periodic transmission lines, microstrip transmission lines, dielectric waveguide

I. INTRODUCTION

Leaky-wave antennas (within the more general class of travelling-wave antennas) are known since many decades; an increasing interest can be stated since the early 1950's, partly based on open homogeneous transmission lines [1-3] or on artificial (periodic) transmission line structures, e.g. [4]. In general, three different configurations of transmission lines for leaky-wave antennas are presently under investigation or even in use – homogeneous lines which are sufficiently "open" and where, according to the respective mode, part of the guided power leaks into free space, periodic or periodically loaded transmission lines where radiation mostly takes place at the involved discontinuities, e.g. [5], and different "artificial" transmission lines which typically are realized involving periodic structures which are small compared to wavelength such that the overall line can be described by averaged properties – typical examples are "left handed" (LH), "composite right and left handed" (CRLH), or "metamaterial" transmission lines [6].

In the following section, a short overview of these types of leaky-wave antennas is given, followed by exemplary antenna realizations in sections III - V.

II. GENERAL TYPES OF LEAKY-WAVE ANTENNAS

A. Leaky-wave antennas based on homogeneous transmission lines

Under certain conditions, homogeneous, sufficiently open transmission lines can leak radiation into free space. The general situation is depicted in Fig. 1 (a). As any portion of the line is contributing to the radiation in phase, the following relations must hold for any value of Δl

$$k_0 \Delta l \sin\vartheta = \beta_{LW}\Delta l \;\text{ or }\; {}^{c_0}/_{v_{ph}} = \sin\vartheta \qquad (1)$$

with β_{LW} the phase constant of the leaky transmission line. Due to the radiation, the propagation constant k_{LW} is complex.

As can be seen from the second part of the equation, the *phase velocity* v_{ph} on the transmission line must be larger than the speed of light in free space c_0 (fast wave). This typically is true for air filled metal waveguide, and if a longitudinal slot is included, it acts as a leaky wave antenna [2, 3]. An example for the application of such an antenna is given in [7] where a longitudinally slotted waveguide is employed in a Doppler radar measuring speed over ground.

As will be discussed in section III, also higher-order modes of planar transmission lines exhibit phase velocities larger than c_0 in a frequency range just above their cut-off frequency.

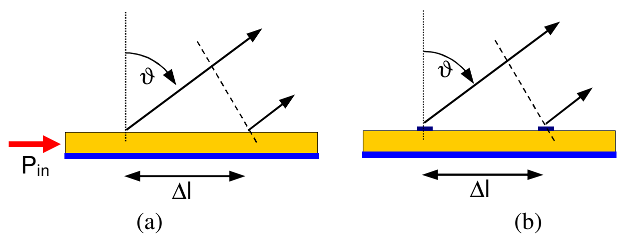

Fig. 1: Principles of leaky-wave radiation.

B. Leaky-wave antennas based on periodical or periodically loaded transmission lines

A second type of leaky-wave antennas is based on periodically disturbed or modulated transmission lines. Typically, radiation in such cases occurs at the discontinuities. For the radiated wave, the contributions from all sources have to be in phase (Fig. 1 (b)), resulting in

$$k_0 \cdot \Delta l \cdot \sin(\vartheta) = k_d \cdot \Delta l + 2\pi n \qquad (2)$$

with k_d the averaged phase constant of the line, Δl the cell length, and n = 0, ±1, ±2 ...

A more general representation of periodic structures is via their periodicity. As the (electric) field along the line fulfills the condition [8]

$$\vec{E}(z)e^{-\gamma\Delta l} = \vec{E}(z+\Delta l) \quad (3)$$

with the imaginary part of γΔl being the phase difference from cell to cell, this distribution can be written as a Fourier series of partial waves (space harmonics or Floquet modes), finally resulting in

$$\gamma_n = \gamma + j\frac{2\pi n}{\Delta l} \quad \text{and} \quad v_{ph\,n} = \frac{\omega}{\beta_n} = \frac{\omega}{\beta+\frac{2\pi n}{\Delta l}}. \quad (4)$$

with $n = 0, \pm1, \pm2...$ Depending on n, phase velocity can be larger than c_0 or even negative. The respective solutions can be calculated either by dividing the structure into unit cells and applying an eigenvalue calculation, e.g. [9], or by direct full-wave calculations, e.g. [10]. In general, periodic transmission lines exhibit normal passbands, stopbands, and leaky-wave regimes in which the propagation constant becomes complex. Group velocity, however, with

$$v_g = \frac{1}{d\beta/d\omega} \neq f(n), \quad (5)$$

is equal for all partial modes.

C. Leaky-wave antennas based on artificial transmission lines

In the last years, metamaterials have gained large interest, including left-handed (LH) or composite right-left-handed (CRLH) transmission lines, e.g. [6]. As such materials with negative ε_r and μ_r do not exist in reality, these have to be approximated by real structures with suitable lumped elements (small compared to wavelength) – e.g. chains with series capacitances and shunt inductances for left-handed lines. As a conventional approach, such structures could equally be described by periodical lines as in section B, but a description by a metamaterial line with averaged properties can give a more compact and straightforward insight into its transmission line properties. The major interest for such transmission lines is the possibility to engineer their phase and phase velocity behavior, exhibiting regimes with normal propagation as well as with negative phase velocities. Accordingly, both with quasi-homogeneous metamaterial lines as well as with lines including additional periodic discontinuities, leaky-wave antennas can be designed for scanning to both endfire and backfire.

III. LEAKY-WAVE ANTENNAS USING THE FIRST HIGHER ORDER MODE OF MICROSTRIP LINES

In 1978, the author of this paper designed a "travelling wave antenna" based on a wide microstrip line and fed with the first higher-order mode [11, 12]. This proved, for the first time, that homogeneous planar transmission lines exhibit leaky-wave behavior. An indication to some kind of "radiation" regime had already been given in [13], and the nature of this phenomenon was explained in detail by Oliner in 1986 [14].

A sketch of the electric field in the cross section of a wide microstrip line is given in Fig. 2, together with a principle diagram of phase constant over frequency. The leaky wave regime exists between the cut-off frequency of the first higher-order mode and the crossing with the curve for k_0. This first higher-order mode can be exited in different ways; already an unsymmetrical feeding with a narrow line excites it to a great extent; a further suppression of the fundamental quasi-TEM mode can be achieved by vias in the center of the wide lines or by transversal slots in the center region affecting only the longitudinal current of the fundamental mode [12]. Alternatively, the two edges of the line can be fed by two signals with opposite phase, e.g. via a rat race coupler (Fig. 3).

Typical normalized radiation diagrams for four different frequencies are plotted in Fig. 4 (measured results). The frequency range is given by the regime indicated in Fig. 2. According to eq. (1), the main beam scans over frequency. On the right side of the diagram (angle > 0°), smaller lobes symmetrical to the main lobes exist due to reflected waves at the (in this case) open end of the line.

Different variations of this type of antenna have been investigated in recent years, including designs with just half the structure (a short circuit at the original center of the line) [15].

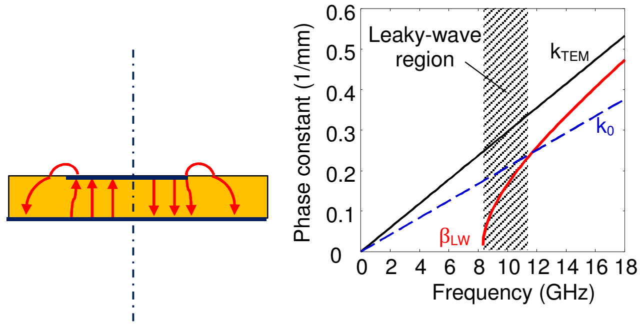

Fig. 2: Cross section with electric field lines and principle behavior of phase constants for free-space propagation (k_0), the quasi-TEM mode (k_{TEM}), and the first higher-order mode (real part β_{LW}).

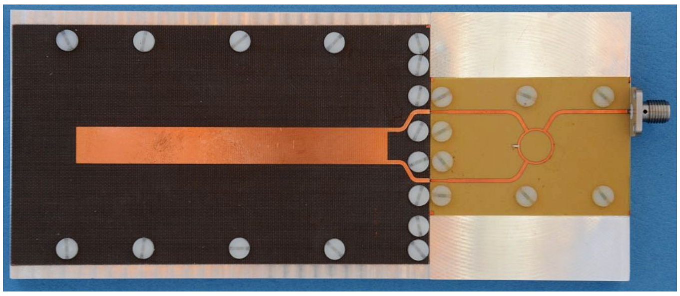

Fig. 3: Photograph of a microstrip leaky-wave antenna with rat-race coupler for feeding. Antenna substrate material: ULTRALAM™ 2000 ($\varepsilon_r = 2.5$, thickness h = 1.52 mm), antenna line width 9.5 mm; substrate material for the rat-race coupler: TMM3 ($\varepsilon_r = 3.275$, thickness h = 0.381 mm).

IV. AUTOMOTIVE RADAR SENSOR INCLUDING A LEAKY-WAVE ANTENNA

An interesting application of a leaky-wave antenna based on a dielectric waveguide with periodic discontinuities can be found in the automotive radar sensor ARS300 designed by Continental ADC (Fig.5, [16]). Ridges on a rotating drum are placed close to a dielectric waveguide forming the required discontinuities; thus the radiated beam is scanned to different directions controlled by the varying ridge distances on the drum. In the orthogonal direction, a planar folded reflectarray antenna [17] focusses the beam; the required polarization grid is integrated on the cover of the sensor not shown in the figure. Radiation diagrams for some selected positions of the drum are plotted in Fig. 6. As the diagrams were recorded with the radar sensor itself, the diagrams represent *two-way* values.

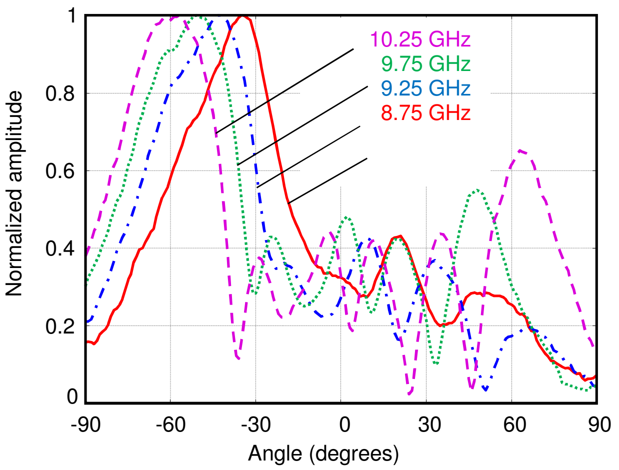

Fig. 4: Experimental H-plane radiation diagrams of the microstrip leaky-wave antenna shown in Fig. 3. 0°.

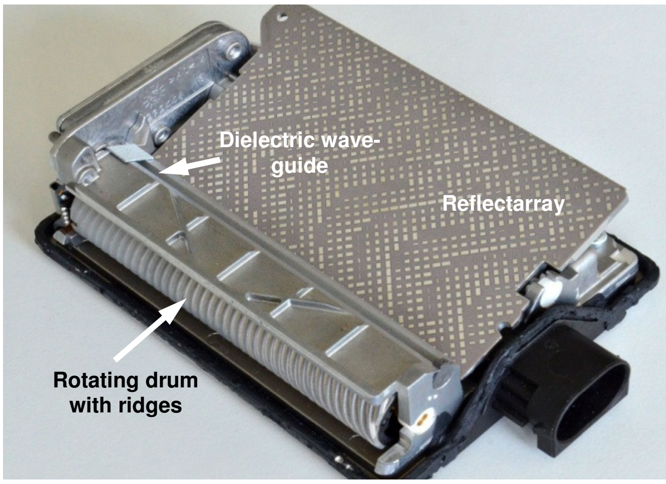

Fig. 5: Photograph of the ARS300 radar sensor with removed cover.

V. Metamaterial Antenna Scanning from End- to Backfire

Left-handed transmission lines with negative phase velocity typically are synthetized using lumped element chains with *series capacitances* C_L and *shunt inductances* L_L. According to the finite size of real elements, *series inductances* L_R and *shunt capacitances* C_R cannot be avoided – resulting in a composite right-left handed (CRLH) transmission line. This artificial transmission line exhibits, depending on frequency, both normal and negative phase velocity. If the ratios L_L/C_L and L_R/C_R are equal, no stopband occurs, and the line is called to be balanced [6]. Phase velocity

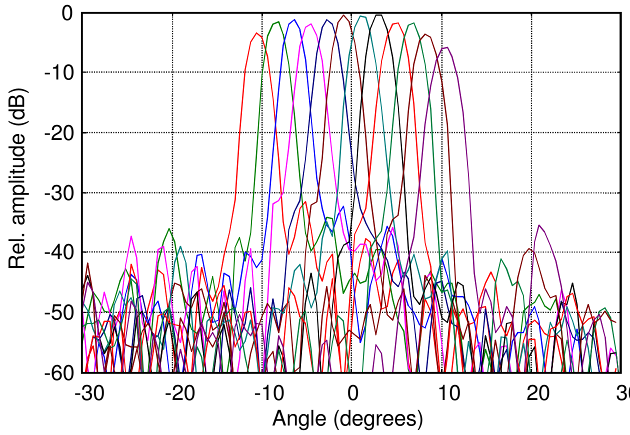

Fig. 6: Two-way azimuth radiation diagrams of the ARS300 antenna for selected drum positions.

$$v_{ph} = \frac{\omega}{\omega/\omega_R - \omega_L/\omega}$$

$$\text{with } \omega_R = 1/\sqrt{L_R C_R}\,,\ \ \omega_L = 1/\sqrt{L_L C_L} \qquad (6)$$

[6] then turns from negative via infinite to positive as a function of frequency, allowing the realization of leaky-wave antennas scanning (over frequency) from backfire to endfire.

For standard microstrip circuits, the necessary shunt inductances require vias to ground, partly difficult to realize for increasing frequencies. A way out of this are structures which are fed symmetrically, exhibiting a virtual ground in the symmetry plane. In this way, a CRLH line may be built by double-T structures as shown in Fig. 7. An increased series capacitance is achieved by a double-layer structure with overlapping metallization. A leaky-wave antenna based on this was presented in [18] for the 3 GHz – 6 GHz frequency range. As no vias are required, this concept can be extended easily to higher frequency. An example is given for the 20 GHz – 30 GHz range; a photograph of this antenna is shown in Fig. 8 [19]. The feeding area is designed such that it includes a balun function, and a 100 Ω resistor is soldered to the end of the line. Measured radiation diagrams for different frequencies are given in Fig. 9. Between 20 GHz – 30 GHz, the beam scans from -50° to +25° with gain values up to 16 dBi.

VI. Conclusion

Three different principles of leaky-wave antennas and three realized designs have been addressed in this paper; more examples are presented in the other contributions of this special session at the EuMC 2013.

Leaky-wave antennas based on homogeneous lines have only a limited design freedom, but do find their applications where the naturally tilted beam is required, e.g. for measurement of speed over ground. Much more design flexibility is found with periodically modulated or metamaterial lines, also in conjunction with reconfigurable or scanning antennas as shown in the second and third example.

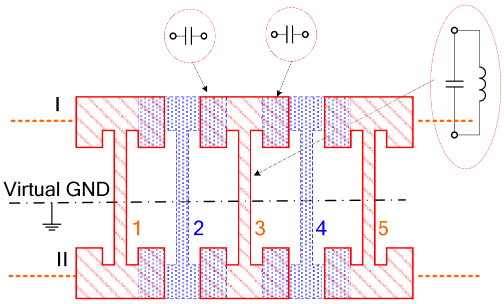

Fig. 7: Structure of the symmetrically fed CRLH structure. Unit elements 1, 3 and 5 (in red, solid lines) are on the top layer, unit elements 2 and 4 (in blue, dashed line) are at the middle metallization layer.

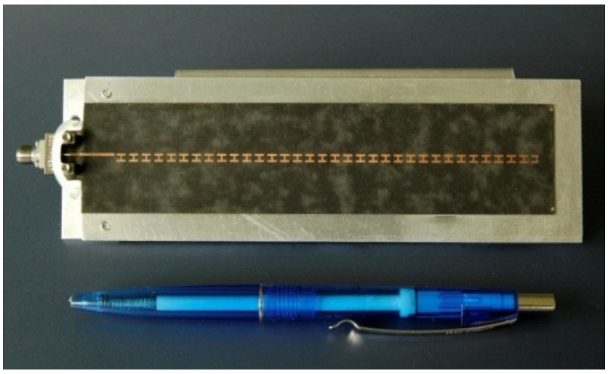

Fig.8: Photograph of the 20 GHz – 30 GHz frequency-scanned leaky-wave antenna.

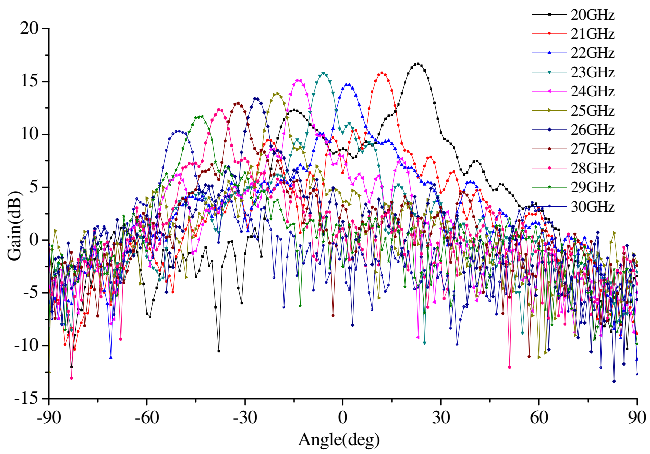

Fig. 9: Measured H-plane radiation patterns of the leaky-wave antenna from 20 GHz to 30 GHz.

REFERENCES

[1] J.N. Hines, V.H. Rumsey, C.H. Walter, "Travelling wave slot antennas," Proc. Inst. Radio Engrs., Vol. 41 (1953), p.1627.

[2] L. Goldstone, A. Oliner, "Leaky-wave antennas I: Rectangular waveguides," IRE Transactions on Antennas and Propagation, Vol. 7 (1959), pp. 307 - 319.

[3] L. Goldstone, A. Oliner, "Leaky wave antennas II: Circular waveguides," IRE Transactions on Antennas and Propagation, Vol. 9 (1961), pp. 280 - 290.

[4] R. Collin, "Analytical solution for a leaky-wave antenna," IRE Transactions on Antennas and Propagation, Vol. 10 (1962), pp. 561 - 565.

[5] T. Itoh, " Application of Gratings in a Dielectric Waveguide for Leaky-Wave Antennas and Band-Reject Filters," IEEE Transactions on Microwave Theory and Techniques, Vol. 25 (1977) , pp. 1134 - 1138.

[6] C. Caloz, T. Itoh, "Novel microwave devices and structures based on the transmission line approach of meta-materials," 2003 IEEE MTT-S International Microwave Symposium Digest, Vol. 1, pp. 195 - 198.

[7] B. Keller, H. Meinel, B. Rembold, B. "vsb-RADAR - A 35 GHz Doppler Radar For Velocity Distance And Acceleration Measurements On Railbound Vehicles," 8th European Microwave Conference, 1978, pp. 598 – 602.

[8] M. Kummer, "Foundations of Microwave Techniques (in German)," VEB, Berlin, 1989, pp. 280.

[9] D. M. Pozar, "Microwave Engineering," 2nd edition, ch. 8.1, John Wiley & Sons, New York, 1998.

[10] Yu-Chiao Chen, C.-K.C.Tzuang, T. Itoh, T. K. Sarkar, "Modal characteristics of planar transmission lines with periodical perturbations: their behaviors in bound, stopband, and radiation regions," IEEE Transactions on Antennas and Propagation, Vol. 53 (2005), pp. 47 - 58.

[11] W. Menzel, "A new travelling wave antenna in microstrip," European Microwave Conf., Paris (1978), pp. 302-306.

[12] W. Menzel, "A new travelling wave antenna in microstrip," AEÜ (Archiv Elektrotechnik Übertragungstechnik), Vol. 33 (1979), 137-140.

[13] H. Ermert, "Characteristics and Radiation Characteristics of Planar Waveguides.," 8th European Microwave Conference, 1978, pp. 94 – 98.

[14] A. A. Oliner, K. S. Lee, "The Nature of the Leakage from Higher Modes on Microstrip Line," 1986 IEEE MTT-S International Microwave Symposium Digest, pp. 57 - 60.

[15] J. Xu, W. Hong, H. Tang, Z. Kuai, Ke Wu, "Half-Mode Substrate Integrated Waveguide (HMSIW) Leaky-Wave Antenna for Millimeter-Wave Applications," IEEE Antennas and Wireless Propagation Letters, Vol. 7 (2008), pp. 85 - 88.

[16] W. Menzel, A. Moebius, "Antenna Concepts for Millimeter-Wave Automotive Radar Sensors (Invited paper)," IEEE Proceedings, Vol. 100, July 2012, pp. 2372 – 2379.

[17] W. Menzel, D. Pilz, R. Leberer, "A 77 GHz FM/CW radar front-end with a low-profile, low-loss printed antenna.," IEEE Trans. on Microw. Theory Tech., Vol. MTT-47, No. 12 (Dec. 1999), pp. 2237 – 2241.

[18] C. Liu, W. Menzel, "Frequency scanned leaky-wave antenna using negative index transmission lines," European Conf. on Antennas and Propagation (EuCAP 2007), November 2007, Edinborough, UK, Paper TuPA.027.

[19] W. Jiang, Ch. Liu, B. Zhang, W. Menzel, "K-Band Frequency-Scanned Leaky-Wave Antenna Based on Composite Right/Left-Handed Transmission Lines," Submitted for publication to the IEEE Antennas and Wireless Propagation Letters.