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Design of a Dual-Mode Operation 2-D Periodic Planar Leaky-Wave Antenna

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Abstract—**In this contribution, we describe the design and the radiation features of a dual-mode operation low-profile, low-cost, wideband antenna. The structure is made by an annular, 2-D radially periodic, leaky-wave antenna enabling the generation of both high-gain beams in the far-field and of nondiffracting waves within the near-field radiative region. This is obtained through the generation of a fast backward spatial harmonic supported by a metal-strip grating placed on a grounded dielectric slab. The radiation can be then described by means of a cylindrical leaky-wave dominating the aperture field of the antenna, whose dispersive behavior is properly taken into account. The high-gain radiation features and the focusing capabilities of the device are experimentally investigated and described. Thanks to the dual-mode capability, the proposed design represents an attractive, simple, and innovative solution for next-generation wireless power transfer devices, for tracking or automotive anti-collision systems as well as for advanced microwave imaging.**

Index Terms—**Leaky waves, near field, dual-mode antennas, wireless power transfer, microwave imaging.**

I. INTRODUCTION

The next-generation of medical imaging and nondestructive testing as well as secure communications, radar and wireless power transfer systems call for the design of low-cost and low-profile antennas enabling advanced performance over both the near- and far-field. Typically, high-directional far-field patterns are obtained by means of arrays of microstrip patch antennas, which can be designed to radiate broadside pencil beams or conical beams steerable along the zenith angle [1]. The elements of the array are conventionally excited by means of parallel or series feeds arrangement, requiring the design of lossy and often complicated feeding networks [2].

Leaky-wave antennas have been demonstrated to be an effective alternative to generate high-gain far-field patterns, thanks to their simple excitation and low-profile intrinsic nature [1, Ch. 11]. At the same time, near-field focused beams can be generated by means of 2-D planar arrays made by horns, patches or by resorting to lens, reflectors, and Fresnel-zone antennas (see, e.g., [3], [4]). A planar array has also been proposed to generate a Bessel beam [5].

A number of alternative design, based on the excitation of the leaky mode supported by an open planar waveguide, have been investigated in the last decade to generate focused beams [6], [7] and Bessel beams [8], [9] within the near-field radiative region of the structure. In [9], it has been demonstrated that a collimated, nondiffracting beam, can also be generated through a ‘bull-eye’ antenna [10], [11] (see Fig. 1), which is made by a periodic annular arrangement of metallic strips over a grounded dielectric slab. This class of structures is, indeed, able to support backward leaky waves that can synthesize an inward traveling-wave on the aperture: if properly excited, this kind of wave can in turn effectively describe the cylindrical aperture field distribution responsible for the radiation [12]. Interestingly, by properly designing the feeding system, ‘bull-eye’ antennas can allow for generating higher arbitrary orders of nondiffracting Bessel beams [9], [13].

Fig. 1. Fabricated and measured planar leaky-wave antenna. Copper color: annular metallic strip arrangement. Dark color: grounded dielectric slab. The structure is made by a slot grating on a grounded dielectric slab (GDS). Strips having width $w = 1$ mm and period $d = 8$ mm define the top PRS. The GDS is made by a dielectric with $\varepsilon_r = 2.2$ and thickness $h = 3.14$ mm.

More recently, the possibility of generating localized waves [14] (i.e., bullet-like pulses) at microwaves by means of a backward cylindrical leaky wave has also been theoretically and experimentally demonstrated by some of the authors in [13] and [15], respectively. In these works, the intrinsic dispersive nature of the complex leaky wavenumber describing the aperture field is taken into account, and its impact on the propagation features of the pulse, with respect to the one generated by the non-planar but very wideband and non-

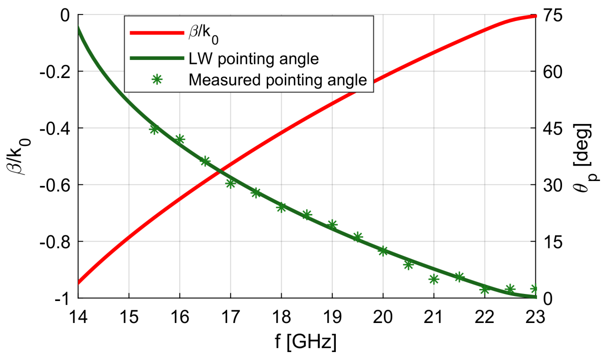


Fig. 2. Left axis: phase constant of the leaky mode supported by the structure in Fig. 1. Right axis: pointing direction of the scanning far-field beam.

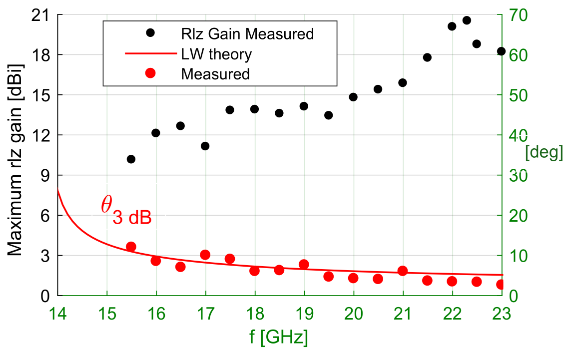


Fig. 3. Left axis: realized gain. Right axis: 3dB beamwidth.

dispersive device presented in [16], is discussed.

Generally speaking, the generation of short microwave pulses, can be used to improve the inherently low resolution dictated by the operating wavelength in conventional radar systems. However, due to their relatively large spectral content, such pulses commonly undergo diffractive spreading as they propagate away from the source (see, e.g., [13], [17] and references therein). Therefore, their generation requires for the introduction of innovative solutions. In this frame, we report here the design and the radiative features of a planar wideband leaky-wave antenna, excited by means of a simple vertical coaxial probe, able to provide an uncommon dual-mode operation. The same structure, indeed, can provide a high-gain scanning conical beam [18], [11], as well as Bessel-beams pattern and bullet-like pulses within the nondiffracting region of the antenna. As discussed in the following, this dual-mode operation can be very attractive for the imaging of concealed objects [19], for the future generation of wireless power transfer system, and for advanced far- and near-field microwave imaging [20], [21].

II. ANTENNA DESIGN

A nth-order Bessel beam can be described by the longitudinal electric-field component of a transverse magnetic wave (TM, with respect to the z axis) $E_z(\rho,\phi,z) = E_0 J_n(k_\rho \rho) e^{-jn\phi} e^{-jk_z z}$, E_0 being an amplitude factor and $J_n(\cdot)$ the nth-order Bessel function, ρ and ϕ the radial and azimuthal coordinates of a cylindrical system, k_ρ and k_z the relevant transverse and vertical wavenumbers. If $n = 0$ the beam is azimuthally symmetric (hence $E_\phi = 0$).

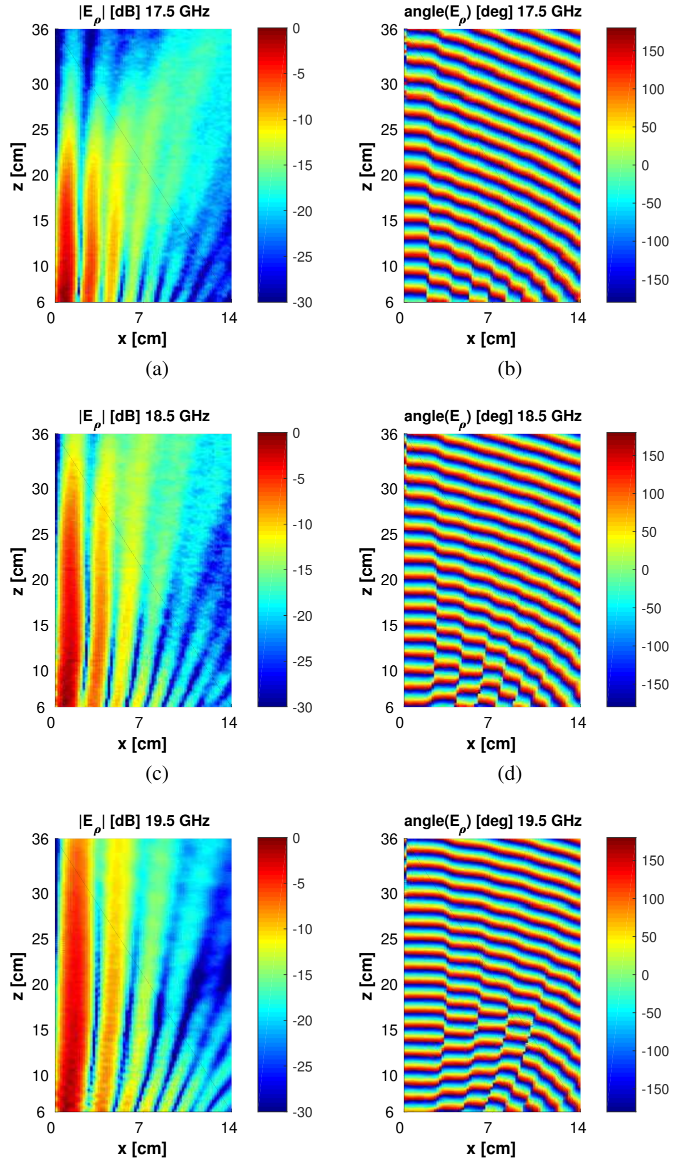
We consider a finite circular radiating aperture of radius ρ_a and orthogonal to the z-axis of a cylindrical system with its origin at the aperture center (see Fig. 1 and [9]). To generate the beam, as discussed in [17], [13], [15], one needs to excite an inward cylindrical wave $H_0^{(1)\prime}(\cdot)$ (first-order derivative of the Hankel function of the first kind). This allows for generating a 0th-order Bessel beam in a region of space close to the z-axis. To synthesize such an inward wave, one can excite an azimuthally symmetric cylindrical TM backward leaky wave [12] supported by an annular slot grating and excited by an azimuthally symmetric source, e.g., a coaxial probe along the z-axis [9]. To this aim we operate in a frequency range where a fast space harmonic exists (the $n = -1$) and is backward, i.e., a proper leaky wave with $\beta_{-1} \cdot \alpha < 0$. The harmonic propagates as an attenuated outward cylindrical wave with $E_\rho \propto H_0^{(2)\prime}(k_{\rho,-1}\rho)$, where $k_{\rho,-1} = \beta_{-1} - j\alpha$, with $\beta_{-1} < 0$ and $\alpha > 0$. Since, in general, $H_0^{(2)}(z) = -H_0^{(1)}(-z)$, the desired aperture distribution is thus obtained [13].

To illustrate the dual-mode operation capability of the proposed antenna, we consider the bull-eye design presented in [9], whose geometrical features are reported in Fig. 1. The structure is properly designed to support an $n = -1$ fast spatial harmonic over an aperture having radius $\rho_a = 14$ cm. Figure 2 reports the normalized phase constant (solid line, left axis) versus the frequency of the linearized structure (see [9] for further details on the linearization aspects). The normalized attenuation constant (not reported here) has a quite stable behavior versus the frequency and is between about 0.02 and 0.035. As experimentally investigated in [11], the antenna radiates a high-directional conical beam, scanning with f and with the main beam covering a wide portion of the upper hemisphere, from about 2° to 70° (see Fig. 2, right axis). The near-field radiated by the prototype has been, instead, investigated in [9], and will be summarized in section III.

III. EXPERIMENTAL CHARACTERIZATION

The dual-mode antenna prototype was measured in a calibrated anechoic chamber. A picture of the structure is reported in Fig. 1, while the impedance bandwidth (well below -10 dB from 14 GHz to 22 GHz) and the configuration of the feed can be found in [9]. Figure 3 reports the main features of the far-field pattern generated by the proposed antenna. The measured maximum realized gain vs. f (black dots, left axis) confirms its high-gain features. Also, its -3 dB beam-width is well predicted by the leaky-wave formula [1, Ch. 11, eqs. 11.2 and 11.3] (red curves, right axis). The beam pointing angle in Fig. 2 (green curves, right axis) is in excellent agreement with the theory.

The normalized z and ρ components of the electric field along the xz plane are reported in Figs. 4 and 5. They are collected moving the probe from 6 cm up to a distance z_0 = 31 cm from the antenna aperture; both amplitude and

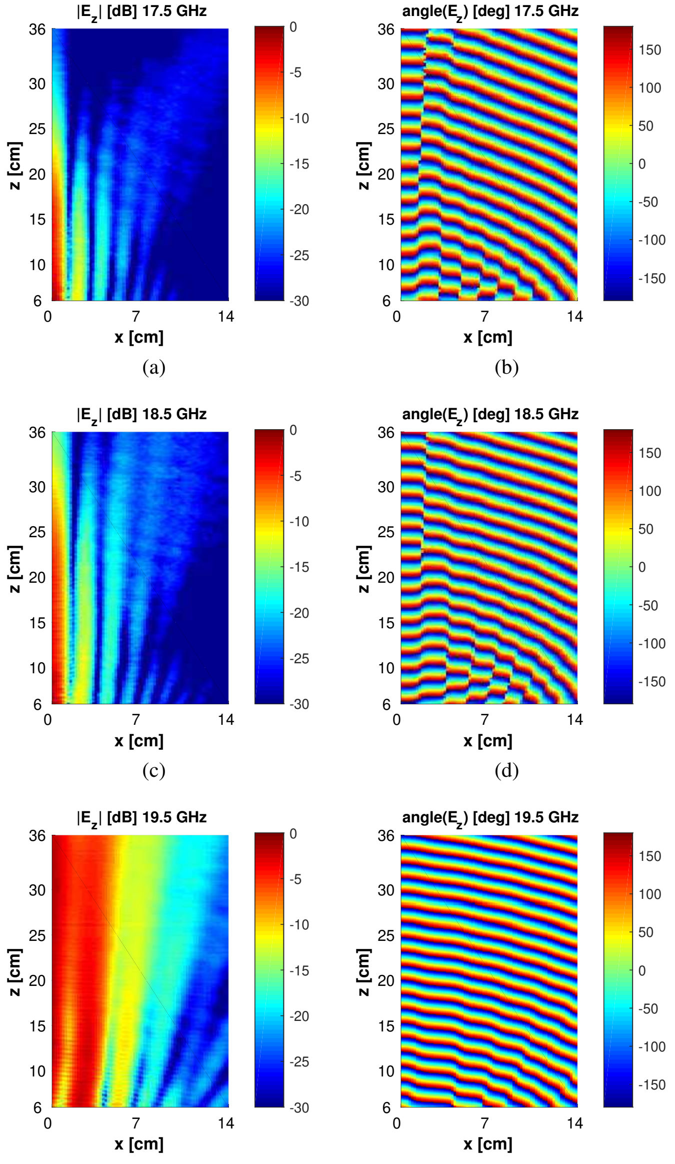


(a) (b)

(c) (d)

(e) (f)

Fig. 4. Measured longitudinal 2-D profile of the near field radiated in the xz-plane (i.e., ϕ = 0) up to z_{NDR} = 31 cm. (a), (c), (e) amplitude and (b), (d), (f) phase of the ρ-component for 17.5, 18.5, 19.5 GHz, respectively.



(a) (b)

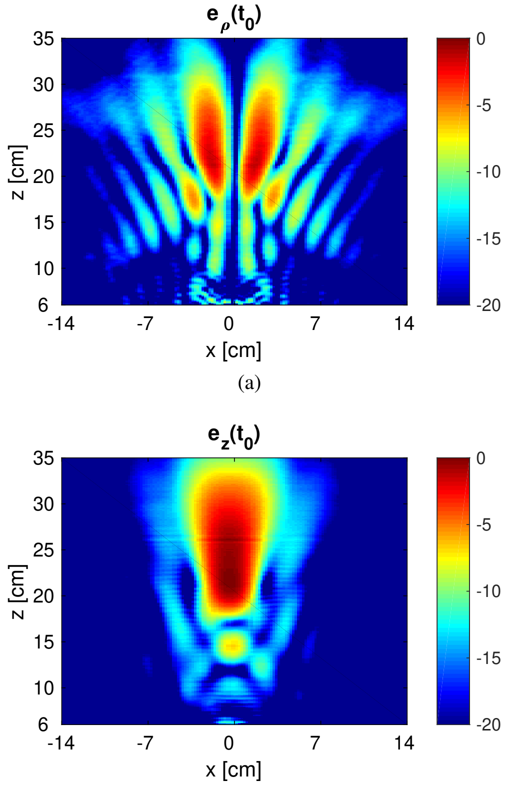
(c) (d)

(e) (f)

Fig. 5. As in Fig. 4 but for the z component of the field.

phase are reported for three different frequencies (see captions, further frequency values and transverse profiles of the field can be found in [9]). As discussed in [9], the antenna is able to generate well defined Bessel-beam patterns over a wide frequency range, enabling the generation of a bullet-like pulse [16] by means of the planar antenna. We should note that, while in far field a variation of the frequency generates a scanning beam over the zenith angle, in the near field it tunes the nondiffracting range of the system [13], and it mainly determines the limit distance beyond which the beam starts to diffract loosing the Bessel-like collimated character.

As experimentally demonstrated in [15], the wideband character of the focusing features of the bull-eye antenna can allow for generating localized energy in the microwave frequency region. However, both the inherent wavenumber dispersion and complex nature of the leaky wavenumber responsible for the radiation unavoidably affects the radiated near field [13]. To assess the uncommon dual-mode operation enabled by the antenna, we exploit here the dispersion engineering approach proposed in [15] to generate a bullet-like pulse within the radiative near-field region of the structure. To this aim, the phase patterns presented in Figs. 4 and 5 have been properly post-processed to provide the requested coherency before performing a fully vector time-domain inversion of the measured near-field maps [15]. Figure 6 reports the amplitude of both the z and ρ components of the field at a time instant $t_0 = 1.1$ ns. The focused character of the pulse is manifest, paving the way for the design of next-generation of highly efficient microwave imaging system based on the use of



(a)

(b)

Fig. 6. Measured normalized leaky pulse field amplitude (dB) over the xz plan: (a) E_ρ (b) E_z for a fixed time instant t_0 = 1.1 ns.

localized energy, as opposed to the more common systems based on the nondirectional character requested to achieve cross-range resolution by means of a synthetic aperture.

IV. CONCLUSION

A wideband radially-periodic, dual-mode operation, leaky-wave antenna fed by a simple source and supporting a fast backward cylindrical leaky wave, has been proposed for generating a highly directional far-field conical beam as well as a nondiffracting beam within the radiative nearfield of the structure. Thanks to the traveling-wave nature of the approach, the capabilities of this class of devices of generating localized pulses in the microwave range have been summarized. The unconventional performance of the proposed devices can offer new ways for the designs of multifunctional antennas: e.g., for wireless power systems requiring both power and data transfer/transmission, and for anti-collision radars with near-field data connectivity. More involved geometry of the aperture will be studied, which can allow for controlling the dispersive behavior of the leaky wavenumber and of the scanning losses. Besides, the use of larger fractional bandwidths will potentially enable for the generation of very short pulses, an attractive features that can open unprecedented possibilities for microwave near-field imaging.

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