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Tunable Terahertz Bessel-Beam Launchers

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Abstract
Bessel-beam launchers are planar devices capable of focusing electromagnetic energy in their radiative near-field region in the form of Bessel beams. Bessel-beam launchers are typically designed to have certain *static* beam features over a given operating bandwidth in the microwave/millimeter-wave range. Here, taking cues from some recent advancements in the field, we propose innovative architectures capable of generating Bessel beams at terahertz frequencies and featuring a *dynamic* control of the cover distance. The ideas outlined in this Vision are expected to pave the way for the realization of the first tunable terahertz Bessel-beam launchers.

Key terms
Bessel beams; focusing; terahertz; leaky waves; tunable devices; metasurfaces

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1. Introduction

Bessel beams are propagation-invariant solutions of Helmholtz equation in cylindrical coordinates [1, 2]. As shown in Fig. 1, a Bessel beam is localized along the transverse plane and the beam waist is preserved along the propagation axis up to a distance known as *nondiffractive range*. Only zeroth-order Bessel beams exhibit a central maximum, whereas higher-order Bessel beams exhibit a central null; the former are attractive in focusing applications [3], the latter instead for multiple input multiple output (MIMO) applications, as they transport orbital angular momentum (OAM) [4]. In the following, however, we only discuss zeroth-order Bessel beams.

Although Bessel beams were first discovered and extensively developed in optics [5], their remarkable focusing and limited-diffraction properties recently raised great interest in the microwave and millimeter-wave domains for their potential application in various contexts such as microwave imaging [6], wireless power transfer [7], etc.

As a matter of fact, the growing interest in the generation of Bessel beams at microwave frequencies has largely promoted their experimental realization in this frequency range (see, e.g., [8] and refs. therein). Planar devices capable of generating Bessel beams at microwave/millimeter-wave frequencies are also known as Bessel-beam launchers. Although there exist now several kinds of Bessel-beam launchers, they can mostly be classified into two categories; traveling-wave wideband launchers (such as radial line slot arrays (RLSAs) [9–11] and leaky

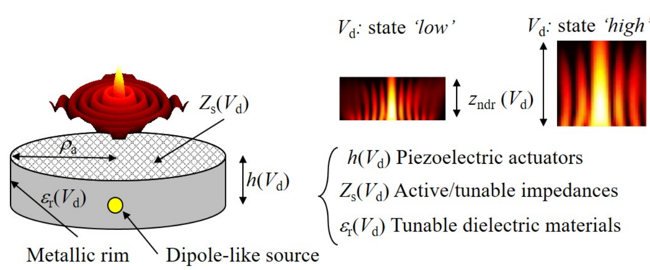

Figure 1: Working principle and possible technological implementations of tunable Bessel-beam launchers. A leaky-wave resonant cavity radiates a Bessel beam whose nondiffractive range z_{ndr} is tuned by acting on a driving voltage V_d that can change: *i)* the cavity height $h(V_d)$ if piezoelectric actuators are used, *ii)* the permittivity of the dielectric filling $\varepsilon_r(V_d)$ if tunable materials are used, *iii)* the sheet impedance $Z_s(V_d)$ if active or tunable metasurfaces are used.

periodic radial waveguides [12, 13]), and standing-wave resonant launchers (such as leaky cylindrical resonators [14, 15]). In both cases, the underlying architecture is a radial waveguide whose upper metallic plate is replaced by a partially reflecting screen (PRS), which allows for radiation.

The main structural difference between *traveling*-wave and resonant launchers is the presence of a circular metallic rim in the latter, which allows for obtaining a *standing*-wave aperture distribution as superposition of outward and inward cylindrical traveling-wave distributions; this gives rise to a radiated Bessel beam in a *conical* region extending from the aperture plane to the nondiffracting range. These structures are usually few wavelengths large, and the PRS is made of a simple *isotropic* metasurface. In traveling-wave launchers instead, the lateral size is usually several wavelengths large, the metallic rim is either absent or replaced by an absorber to avoid reflections, and the PRS is no longer an isotropic metasurface, but rather a *periodic* or more general diffraction grating, which is suitably engineered to synthesize an *inward* cylindrical-wave aperture distribution; this gives rise to a Bessel beam in a *bi-conical* region extending from the aperture plane to the nondiffracting range. A rigorous explanation of these phenomenona can be found in [9, 10, 16].

So far, most of microwave realizations of Bessel-beam launchers (of either resonant or traveling-wave type), did not consider the possibility to equip the device of any *tunable* feature for tailoring the near-field radiating properties. This is a very desirable property that is, instead, extensively investigated for controlling the far-field properties of antennas. While there exists a vast literature on reconfigurable antennas (see, e.g., [17] and refs. therein), few works dealt with the design of tunable Bessel-beam launchers. To the Authors' best knowledge, only few experiments have been performed in the microwave region [18–21]. However, the works in [18–20] require external feeding, whereas that in [21] requires varactor diodes; both solutions would be impractical at THz frequencies for costs, complexity, and losses. As a matter of fact, the realization of tunable Bessel-beam launchers is challenging at any frequency range; at THz frequencies this challenge is heightened by the numerous difficulties that still hinder the efficient generation of Bessel beams with a planar THz device.

In general, THz technology lag behind with respect to microwave technology and photonics, due to relatively limited sensitivity of detectors and available power of sources [22]. With respect to the generation of Bessel beams, the most used technology at THz are Tsurupica axicon lenses [23], that are bulky. One of the few planar solutions proposed so far is a metasurface-based device excited through a slot in the ground plane which is back-illuminated with coherent THz radiation [24]. This solution leads to Bessel beams with hybrid polarization and very low efficiency (around 3%), thus several efforts are needed in this field to achieve a satisfactory performance.

Here, we propose planar THz devices for efficiently generating Bessel beams and equip them of tunable properties. The working principle is outlined in Section 2, and some possible realizations are described in Section 3. The conclusion is finally drawn in Section 4.

2. Working Principle

For the sake of simplicity, we hereafter refer to resonant Bessel-beam launchers, as the one schematically shown in Fig. 1. Such kinds of launchers consist of a grounded dielectric slab of thickness h and relative permittivity ε_{r}, surrounded by a circular metallic rim of radius ρ_{a} and covered on top by an isotropic metasurface, fully characterized by a sheet impedance Z_{s}. The first realizations of such devices [15] were based on the *fundamental* leaky mode supported by the cavity [25], thus allowing low-profile structures, i.e., $h \ll \lambda$, λ being the free-space wavelength. It was later recognized [14] that Bessel beams could be efficiently radiated even by exciting the first *higher-order* leaky mode supported by the cavity, leading to $\lambda/2$-thick dielectric layers. These structures can thus be seen as a *radially* resonant version of Fabry–Perot cavity leaky-wave antennas [26] (FPC-LWAs), which are instead supposed to radially extend for several wavelengths and with an absorber at the cylindrical edge (instead of a metallic rim). This resemblance is extremely important because it allows translating, in principle, most of the concepts of FPC-LWAs to Bessel-beam launchers.

In particular, it is worth noting that there exist several designs of FPC-LWAs with tunable far-field properties (see, e.g., [27–31] and refs. therein). The underlying mechanism is always the same: to induce the variation of the leaky phase constant β by varying the electrical path within the cavity. The physical meaning behind this idea relies in the following expression that relates the antenna beam angle θ_0 to β:

$$\sin\theta_0 = \beta/k_0 \tag{1}$$

where k_0 is the free-space wavenumber. The nonlinear variation of the leaky phase constant with frequency is responsible of the well-known frequency-scanning feature of LWAs [32]. Therefore, in order to tune the pointing angle of the radiation pattern at a fixed frequency one has to gain control on β acting on the geometry and/or the materials of the cavity with an external parameter, e.g., a driving voltage V_{d}.

By the same token, this principle can be extended to control the near-field properties of Bessel-beam launchers. In particular, although in the near-field region the concept of radiation pattern is misleading, the relation in (1) holds true, provided that θ_0 is replaced by the so-called *axicon angle*, a typical parameter of Bessel beams (related to the imposed radial wavenumber on the radiating aperture) that controls their nondiffractive range z_{ndr} and their transverse null-to-null beamwidth S_ρ through the following approximate relations [33]:

$$z_{\mathrm{ndr}} \simeq \rho_{\mathrm{a}} \cot\theta_0 \tag{2}$$

$$S_\rho \simeq 0.765\lambda \csc\theta_0. \tag{3}$$

Consequently, a leaky-wave resonant cavity can be used to generate a Bessel beam whose nondiffractive range is tuned by acting on a driving voltage that can change: *i)* the cavity height h, e.g., by using piezoelectric actuators [27]; *ii)* the permittivity ε_{r} of the dielectric filling, e.g., by using tunable materials, such as liquid crystals [29] or ferroelectric materials [30]; *iii)* the sheet impedance, e.g., by using active or tunable metasurfaces, such as PIN diodes [28] or graphene [31] (see Fig. 1).

To the Authors' best knowledge, the application of these techniques for controlling the near-field properties of Bessel beams has never been proposed in the literature, except for the work in [21], which makes use of varactor diodes technology at microwave frequencies. Some of the abovemenetioned techniques are more amenable than others for a technological implementation at THz frequencies, where planar tunable Bessel-beam launchers are still lacking. The next Section 3 provides some preliminary insights on this possibility.

3. Potential THz Designs

As commented in the Introduction, THz technology poses several challenges (see, e.g., [34]) for the realization of Bessel-beam launchers, even without taking into account tunable features. A relevant aspect is the efficient excitation of the cavity. At microwave frequencies, Bessel-beam launchers are commonly excited with coaxial feeders that are no longer commercially available beyond 110 GHz (the THz ranges starts above 100 GHz) and excite an azimuthally symmetric Bessel beam with transverse magnetic (TM) polarization. The most common type of excitation requires to etch a quasi-resonant slot on the ground plane and to fed it through either free-space coupling or waveguides [34]. Such kinds of excitations lead to lower efficiencies [24] and to Bessel beams with both TM and TE field components; both aspects undoubtedly require further investigations. In this regard, it is worth to mention the intriguing possibility of using multiple sources, e.g., a circular array of either radial or azimuthal slots, to generate higher-order Bessel beams by properly phasing the slots.

With reference to the different techniques that we have listed in Section 2 for implementing tunability in the cavities, the following considerations have to be considered. The use of piezoelectric actuators is effective at microwave frequencies [27], where one needs to tune the cavity height of hundreds of microns to experience a change in the leaky phase constant. At THz frequencies, instead, the wavelength is within 3–300 μm, thus requiring nano-positioners with a precision of microns. Such devices are commercially available (see, e.g., [35]) and may represent a feasible and interesting solution, especially because they do not introduce losses in the system.

In this regard, it is worth noting that the use of tunable materials and/or impedances at THz frequencies is way more critical. For instance, recent efforts in realizing tunable THz FPC-LWAs with either liquid crystals [29] or graphene [31] demonstrated that their dielectric and ohmic losses, respectively, are rather high and most likely prevent from a direct application of these materials to achieve a satisfactory performance.

Nevertheless, one possibility to mitigate losses in Bessel-beam launchers based on liquid crystals or graphene is to compensate these losses by using these materials over a reduced portion of the structure at the expense of a reduced range of tunability. With reference to a Bessel-beam launcher based on liquid crystals, one can think of having a cavity where a thin layer of liquid crystal is sandwiched between two thick low-loss dielectric layers (such as cyclo-olefin polymers [36]). The thickness of the liquid crystal layer can then be optimized so as to obtain the best efficiency vs. tunability trade-off. A similar concept can be applied to Bessel-beam launchers based on graphene [37], where now the losses of graphene can be reduced by defining hybrid metal-graphene metasurfaces as those already proposed in [38, 39]. However, in both cases one has to design a biasing network to effectively tune this material, with the consequent introduction of further losses. All these open non-solved issues (i.e., the mitigation of losses and the integration of the biasing network) make these technologies, although promising, still not mature enough for a prompt realization of a tunable THz Bessel-beam launcher.

4. Conclusion

Bessel beams find applications in a wide range of fields, spanning the entire frequency range from microwave to optics passing through terahertz. In this contribution, we discussed the possibility to realize tunable Bessel-beam launchers at terahertz frequencies, taking cues from microwave designs of reconfigurable Fabry–Perot cavity leaky-wave antennas. Different technologies have been proposed, providing the reader a vision on the most promising trends on this research field.

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