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Towards Terahertz Wireless Authentication with Unique Aperture Fingerprints using Leaky-Wave Antennas

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***Abstract*—We introduce a fundamentally new approach to wireless authentication and fingerprinting based on the unique spectral footprints induced by the geometry of the leakage aperture in the leaky THz waveguides transmitters.**

I. INTRODUCTION

THE frequency-dependent radiations from a THz leaky waveguide (LWG) have recently enabled new paradigms for frequency-controlled beam steering [1], object detection and tracking [2,6], and even concurrent transmission using frequency division multiplexing [3]. Hence, employing parallel-plate leaky waveguides has shown to be promising in the next-generation (beyond 5G) wireless communication and sensing. Here, we explore a new degree of freedom, namely slit shape, in leaky-wave antennas that can play a key role in wireless authentication. In particular, by opening a slit in one plate of a parallel-plate waveguide, we allow the guided wave to *"leak"* energy into free space. The phase-matching requirement for the coupling between the guided mode and free space yields a relationship between the radiation angle (from the slit) and the frequency of guided waves. For the lowest-order transverse-electric (TE1) mode, we can write:

$$f(\phi) = \frac{c}{2b\sin(\phi)} \qquad (1)$$

where b is the plate separation and c is the speed of light. Even though, Eq. (1) accurately models the *peak frequency* at a particular angle, it does not capture the impact of slit geometry. Indeed, most existing works have overlooked the impact of the leaking aperture, with a few exceptions that investigated the impact of slit geometry on coupling efficiency [4].

In contrast, we study the impact of leakage geometry on the spectral profile of radiated signals at any particular angle. Interestingly, the simple monotonic relationship in Eq. (1) does not show any dependency on the slit geometry. Hence, we use Huygen's principle and Fraunhofer diffraction equation to derive the generalized far-field radiation profile from a single-slit parallel-plate waveguide as

$$G(\phi,\theta,f) \propto sinc\left(\frac{W\pi f}{c} sind\,(\theta)\right) sinc\left((\beta(f) - j\alpha - k_0 \cos\phi)\frac{L}{2} \right), \qquad (2)$$

where W is the slit width, L is the slit length, ϕ and θ are the azimuth and elevation angles, respectively. Furthermore, β is the phase constant and α is the attenuation constant. Eq. (2) suggests that changes in the slit geometry of a THz leaky-wave transmitter would leave spectral footprints on the power spectrum at a given angular location (ϕ,θ) relative to the leaky-wave antenna. Our key idea is that such spectral signatures, which is inherent to the characteristic of the leaky transmitter, can be exploited for authentication in THz wireless networks. For instance, consider a scenario in which an adversary launches a spoofing attack by sending falsified data. In this case, the receiver can distinguish the illegitimate transmitter by analyzing the spectrum profile. More importantly, we emphasize that imitating the leaky antenna's aperture-induced fingerprint is almost impossible. This is because estimating the waveguide aperture would require fine-grained measurements at several 3D locations in the vicinity of the legitimate leaky transmitter. In short, the dependency of the spectral fingerprints jointly on the LWG-receiver angular position, as well as the slit geometry, offers two-layer protection against spoofing attacks.

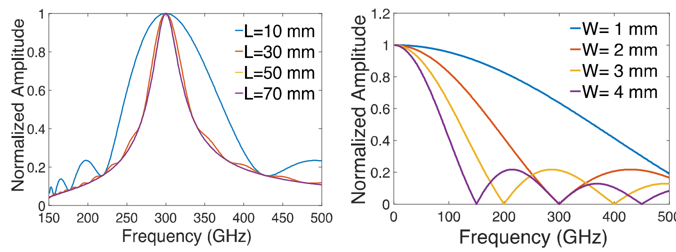

Fig. 1. Leakage geometry as a new degree of freedom to create distinct angular -spectral patterns that can be used for wireless fingerprinting. The figure on the left demonstrates the impact of slit length (L) and the one on the right shows the impact of slit width (W) both using COMSOL simulations.

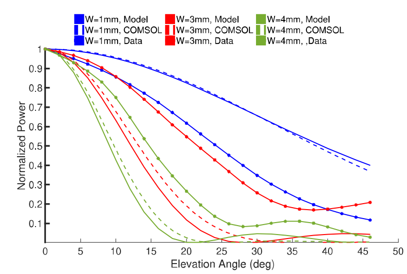

Fig. 2. The experimental evaluation of a single-slit THz leaky waveguide with different slit widths. The trend in experimental data is in good agreement with COMSOL simulations and our model in Eq. (2).

II. RESULTS

To explore aperture-specific spectral fingerprints, we performed COMSOL simulations and over-the-air experiments with a THz time-domain system. Fig. 1 explores the impact of slit length and width separately. First, we consider an LWG with an aperture with a fixed width of 2 mm and vary the slit length from 10 to 70 mm. We can observe that except for L=10 mm, the power spectrum variation is negligible with varying slit lengths. In the special case of L=10 mm (or generally when L < 10W), the slit is not long enough to allow the guided energy to leak out completely. We conclude that employing different slit lengths for the two leakage apertures does not create sufficiently distinct spectral signatures. Yet, this is not the case with the slit width, as shown in Fig. 1. Indeed, the slit width affects the radiated bandwidth from the LWG. Note that in this plot, the elevation angle is fixed to 30 degrees, but a similar trend follows at any other angles. As shown, a narrower slit creates a broader spectral pattern. More importantly, increasing the slit width shifts the spectral nulls to lower frequencies (e.g., 300 GHz for W=2 mm and 200 GHz for W=3 mm). Note that we use a plate spacing of 1 mm which imposes a cutoff frequency of ~ 150 GHz for the TE_1 mode meaning frequencies below 150 GHz could not leak out from the slit.

Fig. 2 confirms the same observation with experimental data. Particularly, we inject a THz pulse into a single-slit waveguide with a slit width of 1 mm, 3 mm, and 4 mm and measure the power distribution across elevation angles at the frequency of 200 GHz. The COMSOL simulation results are consistent with our model in Eq. (2) as well as the collected data. We observe that increasing the slit width decreases the beamwidth of radiation in space (i.e., making it more directional). Hence, manipulating the aperture geometry leaves non-negligible footprints in the spectral-spatial profile of the THz radiations.

We further extend this exploration by simulating apertures that divert from the traditional rectangular slit design. Generally, rectangular apertures have been used in leaky waveguide designs to ensure that the radiated electric field is uniform, which maintains the angle-frequency relation described in Eq. (2). However, one can circumvent this rule by linearly varying the slit width across the waveguide. In particular, Fig. 3 shows a few potential aperture designs where the width is linearly changing along the slit such that it is narrowed at the center and broadened toward the edges. As shown, the starting width (on the edges) varies from 1 mm (resulting in a standard thin rectangular slit) to 5 mm. In simulations, the length of the slit is set to 20 mm and the separation between waveguide plates is fixed at 1mm.

Fig. 4 demonstrates our simulation results with the slit shapes shown in Fig. 3. We demonstrate the spectral profile at various azimuth angles. First, we observe a clear trend in the angle-dependent peak frequencies as suggested by Eq. (2) (the standard 1mm slit has been included in the plot for comparison). These results promise unique opportunities for aperture-based authentication. Specifically, the presence of such irregular sidebands and their key properties (power level, bandwidth, and peak frequency) can facilitate physical layer authentication.

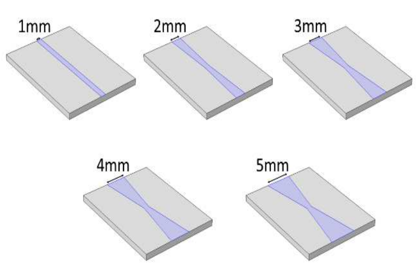

Fig. 3 The simulated aperture designs with rectangular slits of various widths are narrowed in the center and broadened toward the edges.

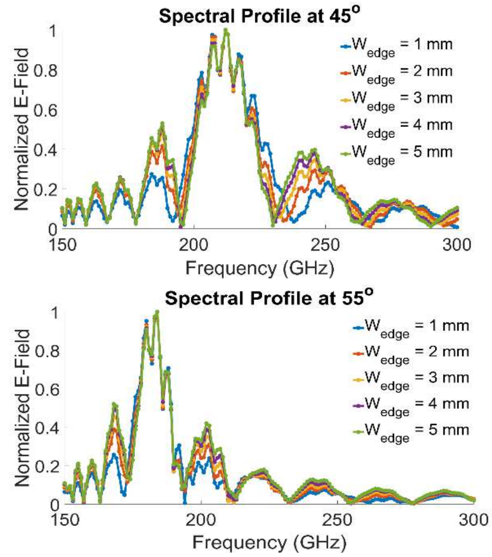

Fig. 4. The simulated spectral profiles correspond to various slit shapes as shown in Fig. 3. The angle-frequency relationship obeys Eq. (2) But we observe irregular and asymmetric sidebands in the spectral profile that can be leveraged as unique aperture-induced fingerprints.

We emphasize that it would be difficult for any adversary to replicate such fingerprints given the sensitivity of spectral profile with mm-scale changes in the leakage aperture. Furthermore, since these emissions are also angle-dependent, an adversary would need to not only know the slit geometry perfectly but also be angularly co-located with the legitimate transmitter, which makes spoofing attacks increasingly difficult, if not impossible.

III. Summary

We have studied the impact of slit geometry on the spectral profile of frequency-dependent radiations from THz leaky antennas. We demonstrate that such non-negligible aperture-induced fingerprints can be leveraged as a physical layer authentication technique to secure the THz wireless networks.

IV. Acknowledgment

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