DEMO: Adversarial Metasurfaces: Metasurface-in-the-Middle Attack

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ABSTRACT

Metasurfaces enable controllable manipulation of electromagnetic waves and have been shown to improve wireless communications in many diverse ways. Investigating adversarial metasurfaces, we define and experimentally demonstrate for the first time a "MetaSurface-in-the-Middle" (MSITM) attack in our paper [1]. In the attack, the adversary Eve places a metasurface in the path of a directive transmission between Alice and Bob and targets to re-direct a portion of the signal towards herself, without being detected. Here, we demonstrate the rapid fabrication of the MSITM employing only standard office supplies such as a printer, paper, foil, and laminator. We show that an effective metasurface can be prototyped in under 5 min at the cost of several cents. We also demo the attack implementation in the THz network, presenting a video of the MSITM attacker establishing a diffractive eavesdropping link while maintaining the legitimate Alice-Bob link. Our results indicate that the attack yields an acute eavesdropping vulnerability while leaving a minimal energy footprint, making the attack challenging to detect.

CCS CONCEPTS

• **Security and privacy → Mobile and wireless security**.

KEYWORDS

Adversarial Metasurfaces, Physical Layer Security, Terahertz

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1 INTRODUCTION

Metasurfaces are artificially engineered structures that exhibit customizable electromagnetic properties, even beyond what is available in nature [2]. Metasurfaces have been used to enhance wireless communication performance in numerous ways, e.g., relaying signals via transparent metasurfaces embedded in windows [3] and extending signal coverage through metamorphic surfaces on curtains and blinds [4]. With the advancement towards 6G networks, metasurfaces are envisioned to become an even ubiquitous part of the environment [5–7], providing highly controllable steering capability of high data rate (Tb/sec), high directional, and high-frequency (0.1 to 1 THz) wireless links. Moreover, the Federal Communications Commission (FCC) has adopted regulations in 2019 to expedite the development of new services in the spectrum above 95 GHz [8] and high data rate THz transmission over a distance of more than 1 km has already been demonstrated [9, 10].

In our paper [1], we consider for the first time that the *adversary* employs a metasurface and explore a new acute vulnerability to a diffractive *MetaSurface-in-the-Middle* (*MSITM*) attack. In particular, we show how Eve can design and deploy a diffractive metasurface to secretly intercept and manipulate EM waves of Alice's transmission. Eve alters the radiation pattern between Alice and Bob to simultaneously *(i)* establish a diffracted link directed towards Eve so that Eve can be located away from Alice and Bob and *(ii)* maintain Alice and Bob's legitimate communication link so that Eve can avoid detection. In this work, we demonstrate key aspects of [1] including rapid fabrication of MSITM and a video of an experimental demonstration of the MSITM attack in the THz network (the THz equipment is on an optical table that is expensive to transport).

2 ATTACK OVERVIEW

To carry out the attack, Eve develops a metasurface that can diffract THz transmission and position it between Alice and Bob, possibly hiding it in the environment as a "bug," e.g., disguising it as a part of

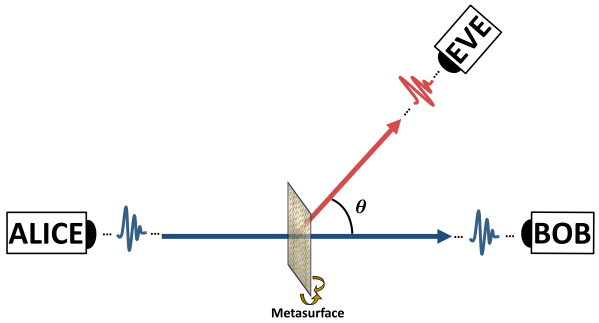


Figure 1: Overview of the MSITM attack

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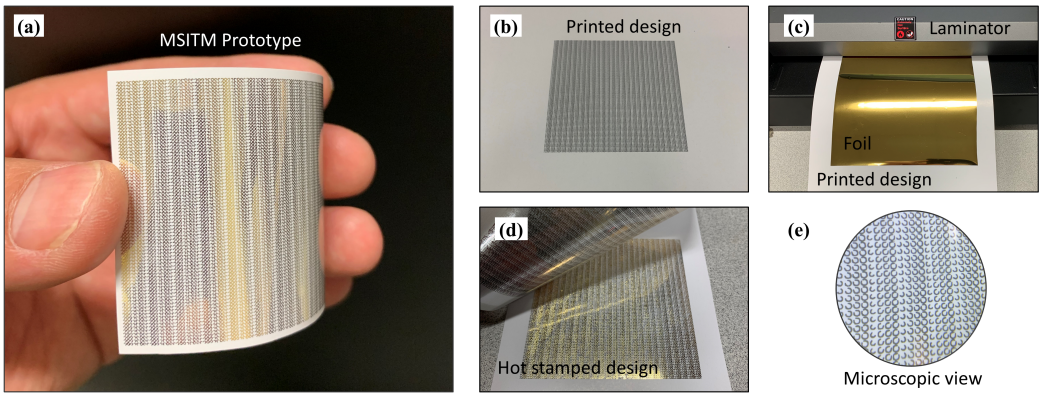


Figure 2: (a) is a prototype of the MSITM. Eve employs a low-cost and rapid fabrication method that involves (b) printing the designed pattern and (c) passing printed paper patterns along with metallic foil through a laminator. The surface (d) can also be cleaned with tape to remove excessive foil powder. (e) is a microscopic view of the fabricated metasurface.

the decoration or concealing it among other objects in the area. As depicted in Figure 1, Alice's signal propagates in the medium and passes through the metasurface before reaching Bob. The center of the surface is designated as the origin of the coordinate system and θ corresponds to Eve's angle relative to Bob and γ represents the incidence angle of the transmission.

To deflect a portion of Alice and Bob's transmission towards herself, Eve designs a metasurface that introduces a phase discontinuity at the surface interface. Specifically, she purposefully induces abrupt and position-dependent phase changes $\Phi(x)$ at the metasurface. Eve's engineered radiation pattern beyond the surface enables her to control the angular direction of the eavesdropping link based on generalized Snell's law as:

$$\theta = \sin^{-1}\left(\frac{\frac{c}{2\pi f_c}\frac{d\Phi(x)}{dx} + n_\gamma \sin(\gamma)}{n_\theta}\right) \quad (1)$$

where $\frac{d\Phi(x)}{dx}$ is the gradient of phase discontinuity, γ denotes the angle of incidence relative to the surface norm, f_c is the center frequency and c is the speed of light. Also, n_γ and n_θ are refractive index the propagation medium. In [1], we the discuss design space of the attacker in achieving her targeted phase discontinuity $\Phi(x)$ and describe how Eve constructs subwavelength scale metallic resonators (meta-atoms) to control the amplitude and phase of the transmission according to geometrical configurations and orientations of the meta-atoms.

3 MSITM FABRICATION

Traditionally, methods such as photolithography [11] are employed to fabricate metasurfaces. However, they are also costly and complex. Instead, we consider an adversary that exploits recent inexpensive and rapid fabrication alternatives such as the hot-stamping technique [12]. Convenient for Eve, the technique requires only standard office supplies, specifically, a toner-based printer, standard laminator, glossy paper, and inexpensive metallic foil. The adversary prints the design patterns on paper and then deposits metallization powder from the foil into the printed pattern. By doing so, Eve generates a metasurface with carefully arranged metallic structures on the THz transparent paper substrate as depicted in Figure 2(a). Consequently, she can controllably scatter an impinging transmission and establish diffracting eavesdropping links with that metasurface.

To prototype the MSITM, we first print the designed pattern using a Brother HL4150cdn printer and Hammermill glossy paper as shown in Figure 2(b). Next, we place an inexpensive iCraft Deco foil sheet on top of the printed pattern and pass it through a standard TruLam laminator at 263°F temperature, illustrating the process in Figure 2(c). With the foil containing a nearly 40μm thick layer of aluminum-based metallization powder, heat and pressure from the lamination allow the powder and toner to bond together. As a result, the metallic layer transfers on the printed pattern as shown in Figure 2(d). Several iterations of lamination could be performed to yield better bonding. Finally, the excess powder can be removed from the surface by cleaning it using tape. Importantly, Eve can quickly and cheaply fabricate the MSITM, spending less than 5 min per surface and employing only standard office items.

4 EVALUATION

4.1 Experimental Setup

We conduct the MSITM attack experiments using a TeraMetrix T-Ray 5000 TD-THz system [13]. The system has two fiber-coupled sensor heads acting as a transmitter and receiver. The terahertz transmitter generates wideband terahertz pulses that are received in real-time by the terahertz receiver. We place the transmitter and the receiver 1m apart from each other (due to the system's sub-μW transmit power) while positioning the fabricated metasurface 50cm from the transmitter. We consider Alice and Bob communication with f_c = 150 GHz and bandwidth B = 30 GHz, and Eve positions herself at the empirically optimal angular location 22°.

4.2 Eve's Reception

Without a metasurface to alter Alice's highly directional transmission, Eve largely observes noise fluctuating at around normalized

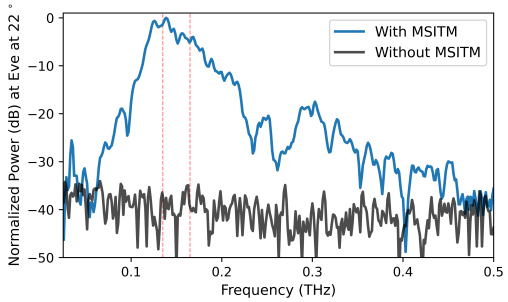


Figure 3: Eve with and without MSITM

power of −40 dB as illustrated in Figure 3. However, we discover that Eve can deflect a significant signal power to herself when she employs the MSITM in the attack. Indeed, observe that her metasurface enables her to receive over 30 dB more signal power relative to the baseline at her targeted center frequency. Thus, she can establish a diffraction peak eavesdropping link and compromises Alice and Bob's link secrecy.

Moreover, Eve receives non-negligible power at many other frequencies even though the device under test is specifically designed for her targeted $f_c = 150$. In particular, she acquires a very large range of communication bands spanning between $50 - 450$ GHz. Even at a further 450 GHz, she obtains a power increase of approximately 8 dB as shown in Figure 3. However, if, for instance, Alice and Bob were communicating at 450 GHz in the first place, Eve would not simply lose the remaining 22 dB, but would rather prefer to have the metasurface redesigned. Particularly she would employ Equation (1) and reconfigure meta-atoms to be optimized for the different f_c as we describe in [1].

4.3 Impact at Bob

We explore the impact of the MSITM attack on Bob, as disruption to Bob's communication link could alert him to the attack. In particular, we analyze the degradation of transmission power at Bob due to the presence of the MSITM in the path of the Alice-Bob link.

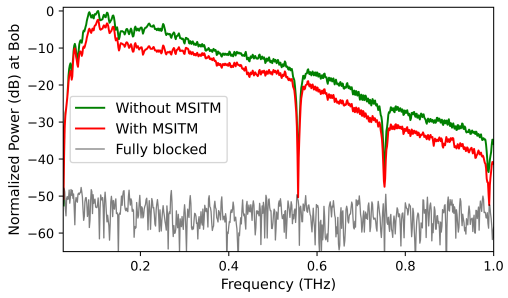


Figure 4: MSITM attack from perspective of Bob

We discover that the power spectrum observed by Bob with MSITM is quite similar to the one when there is no MSITM, with a modest some downward shift shown in Figure 4. Indeed, the fluctuations of the red curve closely resemble the changes in the original green one across different frequencies. Thus, at Bob, the MSITM induces only a few dB power reduction that is nearly uniform across the spectrum. This indicates that Eve's MSITM attack is quite efficient and effective in deflecting power to herself such that Bob experiences only a few dB ($3 - 4$ dB) signal power loss at his end and the dynamics of the power spectrum he observes with and without the metasurface is not easily distinguishable.

Unfortunately for Alice and Bob, a few dB power loss is characteristic of many wireless channels and would be unlikely to impact Alice and Bob's beam steering decision. In fact, slight distance change between communicating entities, such as minor mobility, also causes a similar few dB path-loss shift, which is especially common at these high THz frequencies. Similarly, antenna misalignment, e.g., small-scale orientation change, can yield similar effects. Thereby, Eve leaves a minimal attack footprint, making the attack both devastating and challenging to detect.

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