

The Design and Development of Wideband Time-Modulated Frequency- Selective Surfaces with Transmission Windows for Radar Countermeasures of Communicating Devices

Baisakhi Bandyopadhyay, *Graduate Student Member, IEEE*, Kumar Vaibhav Srivastava, *Senior Member, IEEE*

Abstract—This work presents a polarization-insensitive wideband time-modulated frequency selective surface (TM-FSS) for radar countermeasure applications in microwave antenna systems. The proposed TM-FSS operates over 0.8–2.4 GHz, covering the L-band and part of the S-band with 100% fractional bandwidth. The unit cell is designed to provide a wideband transmission response, enabling wireless radiating devices to be placed beneath the structure for radar concealment applications while ensuring uninterrupted antenna operation. To investigate the out-of-band performance, an X-band microstrip antenna array operating at 8 GHz is integrated with the proposed TM-FSS. Such a configuration is particularly suitable for airborne platforms, where X-band antennas are used for communication while ground-based radar systems commonly operate in the L- and S-bands for target detection. The TM-FSS and integrated antenna array are fabricated and experimentally validated, and the measured results show good agreement with simulations.

Index Terms—Time modulated FSS, Doppler radar countermeasure, microwave antenna, wideband transmission.

I. INTRODUCTION

FREQUENCY selective surfaces (FSSs) have been widely investigated for their capability to control the transmission and reflection, and absorption of electromagnetic (EM) waves and are extensively utilized in stealth and radar countermeasure applications [1]. Recently, TM-FSSs have attracted significant attention due to their ability to dynamically manipulate the reflected spectrum and generate additional harmonics or sidebands [2]–[3]. Such structures are highly promising for Doppler radar countermeasure applications, as they can distort the actual Doppler information of moving targets [4]–[5]. Several TM-FSS metasurface designs have been reported for applications such as frequency conversion, passive false target spoofing [3], spectral camouflage [6], and radar characteristic manipulation [7].

However, most of the reported works mainly focus on metallic targets or standalone metasurface structures, while very limited attention has been given to the concealment of practical communication antennas mounted on airborne platforms. In realistic scenarios, the communication antenna itself remains exposed to hostile radar systems and can reveal valuable Doppler and motion-related information. To address

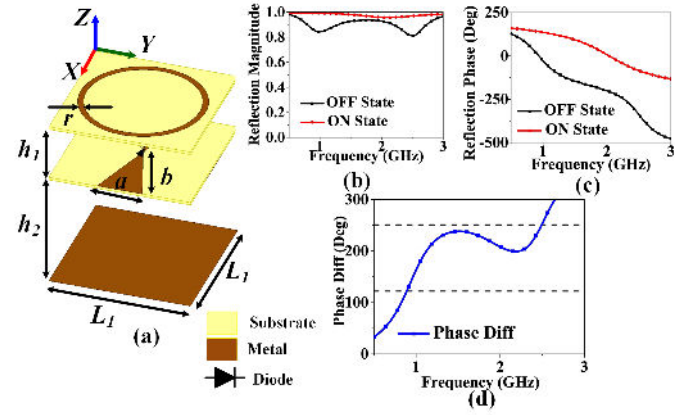


Fig. 1. (a) Isometric view of the proposed unit cell, where $r = 1$, $L_1 = 25$, $h_1 = 10$, $h_2 = 20$, $a = 8$, $b = 12.59$ (units: mm), unit cell responses, (b) reflection magnitudes in both ON and OFF states, (c) reflection phases in both ON and OFF states, (d) phase difference between the ON and OFF states

this challenge, this work presents a polarization-insensitive wideband TM-FSS operating from 0.8–2.4 GHz for radar countermeasure applications, where the unit cell is specifically designed to provide a wideband transmission response so that a communicating X-band antenna can be placed beneath the structure without degrading its radiation performance. The proposed approach experimentally demonstrates the concealment of a functioning communication antenna using a wideband TM-FSS while simultaneously enabling Doppler spoofing characteristics [8].

II. DESIGN ANALYSIS

The proposed TM-FSS is designed by combining a switching middle layer with a transmissive top filter layer to achieve wideband operation and antenna integration capability. The switching behavior is mainly controlled by the PIN diode integrated within the middle layer. In the ON state, the PIN diode behaves as a low-resistance path, causing the incident electromagnetic wave to reflect from the switching layer itself. In the OFF state, the diode behaves as a high-resistance path, allowing the wave to propagate toward the bottom metal ground plane before reflection. This switching mechanism creates a continuous phase difference between the ON and OFF states, which is essential for time modulation and sideband generation, as shown in Fig.1. For effective time modulation, the phase difference should remain within

This work was supported in part by the IEEE Microwave Theory and Technology Society (MTT-S) through the IEEE MTT-S Graduate Fellowship 2025.

B. Bandyopadhyay and K. V. Srivastava are with the Department of Electrical Engineering, Indian Institute of Technology Kanpur, Kanpur 208016, India (e-mail: baisakhi20@iitk.ac.in; kvs@iitk.ac.in).

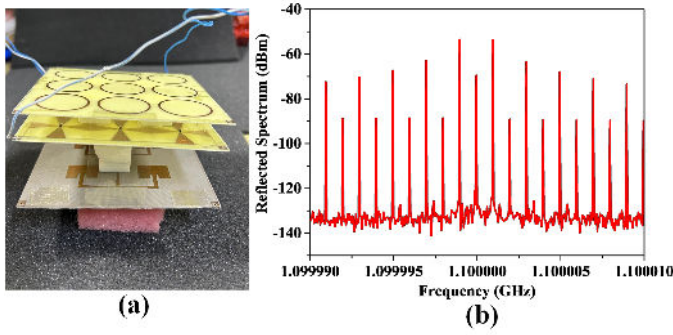


Fig. 2. (a) Fabricated proposed FSS structure integrated with the antenna array, and (b) measured reflected spectrum at 1.1 GHz for the proposed fabricated FSS integrated with the antenna array.

115° – 245° , ensuring that the first-order sidebands become stronger than the fundamental reflected component.

To investigate the transmission characteristics, the back metal layer is removed and two Floquet ports are introduced. The obtained responses verify a wide transmission band extending from 6–10 GHz and beyond for both ON and OFF states. Based on this transmission response, an 8 GHz microstrip antenna array is selected and integrated beneath the proposed TM-FSS. The top transmissive layer is further optimized along with the air gaps to achieve a wide operational bandwidth of 0.8–2.4 GHz with polarization-insensitive performance, while maintaining proper radiation characteristics of the integrated antenna system.

III. RESULTS AND DISCUSSIONS

After verifying the complete structure through full-wave simulations, the proposed structures were fabricated and experimentally characterized. Initially, the TM-FSS structure was measured using a metallic ground plane to validate its time-modulation and sideband generation characteristics. The measured reflected spectra confirmed the suppression of the fundamental component along with the generation of stronger first-order sidebands, as shown in Fig.2.

Subsequently, the metallic ground plane was removed and replaced by the fabricated planar X-band antenna array, where the antenna ground plane acted as the common ground plane for the complete structure. The measured antenna responses demonstrated stable impedance matching, radiation patterns, and realized gain in both ON and OFF states. The measured results closely matched the simulated responses, confirming that the proposed TM-FSS effectively conceals the communication antenna while maintaining its radiation performance [8].

IV. CONCLUSION

This work presented a polarization-insensitive wideband TM-FSS for radar countermeasure applications. The proposed structure operates from 0.8–2.4 GHz and enables the concealment of an X-band communication antenna without degrading its radiation performance. The designed TM-FSS generates strong sidebands for Doppler spoofing while maintaining a

wideband transmission response for the integrated antenna system. The proposed structure was fabricated and experimentally validated, and the measured results showed good agreement with the simulations, demonstrating its suitability for practical airborne stealth applications.

V. IMS 2025 IMPRESSIONS, FELLOWSHIP IMPACT, AND CAREER PLAN

IMS 2025 was an incredible and memorable experience for my professional growth in RF and microwave engineering. As this was my first IMS, the experience was truly inspiring. The symposium offered highly informative technical sessions and opportunities to interact with leading researchers, scientists, and industry experts from around the world. The Women in Microwaves session was especially motivating and encouraging. Another major highlight was the massive exhibition area with numerous industrial sponsors and advanced technology demonstrations, which was unlike anything I had experienced before. Interacting with experts, exploring emerging technologies, and engaging with exhibitors made the event exceptionally enriching. I truly believe that every RF engineer should experience IMS at least once in their career. The IEEE MTT-S Graduate Fellowship played a crucial role in fulfilling my dream of attending IMS 2025, which would have been very difficult otherwise due to the high travel expenses from India.

Currently, I am associated with IIT Kanpur as a FARE Fellow, continuing my research in RF and microwave engineering. My long-term goal is to pursue a career in academia. Before that, I aspire to gain international research exposure through a postdoctoral position, which I am currently exploring.

REFERENCES

- [1] B. A. Munk, Frequency selective surfaces: theory and design. John Wiley Sons, 2005.
- [2] M. Saikia, K. V. Srivastava, and S. A. Ramakrishna, "Frequency-shifted reflection of electromagnetic waves using a time-modulated active tunable frequency-selective surface," *IEEE Transactions on Antennas and Propagation*, vol. 68, no. 4, pp. 2937–2944, 2020.
- [3] M. Saikia, K. V. Srivastava, and S. A. Ramakrishna, "A polarization-insensitive time-modulated frequency-selective surface for broad frequency range," *IET Microwaves, Antennas Propagation*, vol. 16, no. 1, pp. 37–45, 2022.
- [4] X. Fang, M. Li, S. Li, D. Ramaccia, A. Toscano, F. Bilotti, and D. Ding, "Diverse frequency time modulation for passive false target spoofing: Design and experiment," *IEEE Transactions on Microwave Theory and Techniques*, vol. 72, no. 3, pp. 1932–1942, 2024.
- [5] D. Ramaccia, D. L. Sounas, A. Al'u, A. Toscano, and F. Bilotti, "Phase-induced frequency conversion and doppler effect with time-modulated metasurfaces," *IEEE Transactions on Antennas and Propagation*, vol. 68, no. 3, pp. 1607–1617, 2020.
- [6] X. Wang and C. Caloz, "Spread-spectrum selective camouflaging based on time-modulated metasurface," *IEEE Transactions on Antennas and Propagation*, vol. 69, no. 1, pp. 286–295, 2021.
- [7] G. Sun, J. Wang, S. Xing, D. Huang, D. Feng, and X. Wang, "A flexible conformal multifunctional time-modulated metasurface for radar characteristics manipulation," *IEEE Transactions on Microwave Theory and Techniques*, pp. 1–15, 2023.
- [8] B. Bandyopadhyay, R. Vishwakarma, M. Saikia and K. Vaibhav Srivastava, "Polarization Insensitive Wideband Time-Modulated Frequency Selective Surface: An Approach for Radar Countermeasure of Microstrip Antenna," in *IEEE Transactions on Antennas and Propagation*, vol. 74, no. 3, pp. 2420–2430, March 2026, doi: 10.1109/TAP.2025.3647969.