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A dual-band wireless communication of spoof plasmonic meta-waveguide

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The ever-growing demands in wireless communications, computational imaging, and light detection necessitate the capability to freely manipulate electromagnetic waves. Miniaturized and highly integrated devices hold great promise for the future of communications. Spoof plasmonic metamaterials, in particular, have shown potential in creating functional devices and systems due to their ultra-compact and low-profile advantages [1–3]. Spoof surface plasmon polaritons (SSPPs) have garnered significant attention for their flexible dispersion behaviors, enabling advanced manipulation of electromagnetic (EM) waves and real-time digital information processing [4]. However, previous efforts to convert surface waves into radiation waves have focused primarily on overall regulations, overlooking the potential of richer coding regulation strategies that could lead to more flexible and efficient forms of information modulations.

Here, we propose a programmable spoof plasmonic meta-waveguide that leverages its low-profile and ultra-compact design to achieve dual-band wireless communications, as shown in Figure 1(a). The proposed SSPP meta-waveguide consists of 40 SSPP units loaded with positive-intrinsic-negative (PIN) diodes. Detailed structural parameters can be found in Appendix A. Owing to the flexible dispersion behaviors of SSPPs, the surface impedance can be manipulated by switching the "OFF/ON" state of the PIN diode, as shown in Figures 1(b) and (c). This provides a precondition for realizing dual-band radiations at the operating frequencies f_1 and f_2 (in Regions I and II). To bridge between the analog and digital systems, the "ON" and "OFF" states of the PIN diodes are digitized into "0" and "1" states. The modulation period and average impedance can then be adjusted by independently and periodically switching each SSPP unit's "0/1" states using a field programmable gate array (FPGA). For instance, if the target USERs 1 and 2 operate at frequencies of 14 and 24 GHz (f_1 and f_2), respectively, and their corresponding radiation regions are approximately -20° and 21.3°, the theoretical coding sequence is "00110011..." (see Appendix B for detailed analysis) [5]. To enable simultaneous and independent control of the two users, three additional coding sequences ("011100111...", "0001000100011...", and "0000...") are utilized. For simplicity, we label these sequences as V3, V2, V1, and V0. Through calculations, we determine that two users in the V3–V0 states correspond to 2-bit digital coding states ("11, 10, 01, 00"). In this coding scheme, the binary symbol "1" represents instances when the user's region coincides with the marked radiation region and the radiated intensity is sufficient. Conversely, the binary symbol "0" is used otherwise.

To verify the above theoretical analysis, we simulated the proposed SSPP meta-waveguide. As expected, the scheme enables simultaneous and independent transmission of different EM information to two users in distinct regions (detailed in Appendix B). Following the simulation, we fabricated a sample of the SSPP meta-waveguide and set up an experimental demonstration in a microwave anechoic chamber (details in Appendix C). We employ a 2-amplitude-shift-keying modulation scheme to obtain radiation patterns for V3–V0, shown in Figure 1(d), in which the shaded regions indicate the positions of the target users. In the V3 state, both USERs 1 and 2 in their respective regions receive EM signals from the SSPP meta-waveguide. In the V2 state, only USER 1 receives the EM signals, whereas USER 2 does not. Conversely, in the V1 state, only USER 2 receives the signals, and USER 1 does not. When the coding sequence is V0, with all PIN diodes switched off, neither USERs 1 nor 2 receives signals from the SSPP meta-waveguide. The measured results confirm that it is possible to independently shape dual-band free-space waves by switching a 1-bit digital coding sequence.

To showcase the concept and capability of the proposed SSPP meta-waveguide, we established a wireless communication system in an indoor setting (details in Appendix D). Based on our analysis, USERs 1 and 2, represented by two received antennas, are positioned in the designated target directions. Two images (shown in Figure 1(a)) are initially encoded into digital signals with binary sequences to facilitate data stream transmissions. These 2-bit data streams are then converted into the control signals to drive the proposed SSPP meta-waveguide. The FPGA transforms the users' intended code into the corresponding coding sequence

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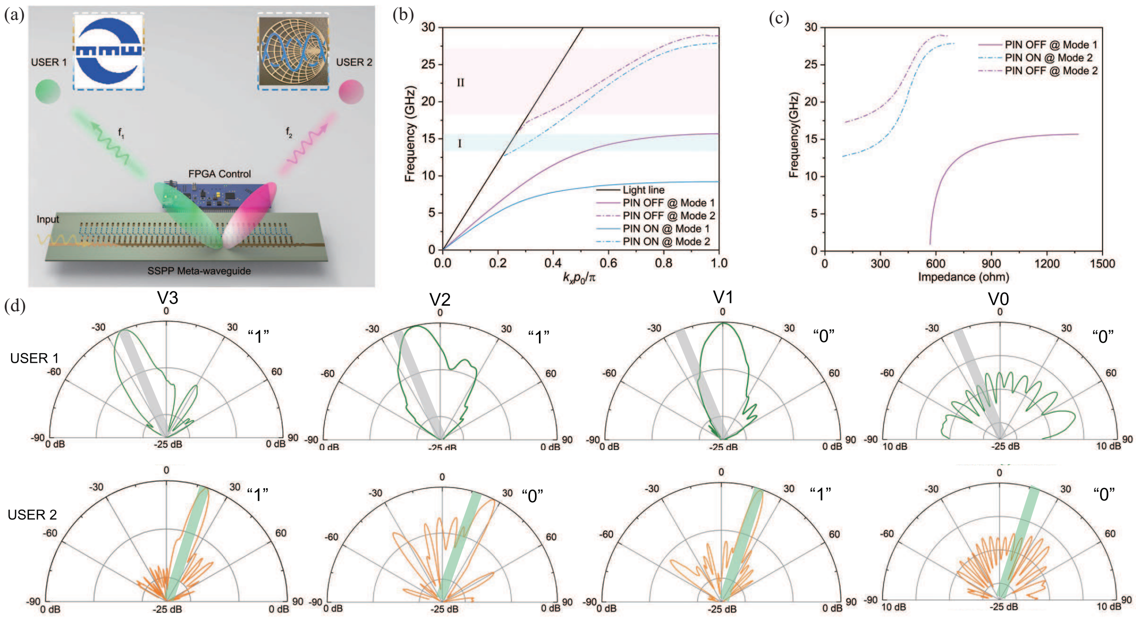

Figure 1 (Color online) SSPP meta-waveguide using a dual-band wireless communication. (a) Conceptual illustration of the programmable SSPP meta-waveguide; (b) dispersion behaviors; (c) the surface impedance; (d) measured patterns in V3, V2, V1, and V0 states.

and applies the driving voltage to the appropriate SSPP unit via the FPGA's input-output port, switching the PIN diode states accordingly. Once the images are converted into a binary coding sequence, the carrier signals carrying the two data streams are sequentially emitted by the proposed SSPP meta-waveguide. The radiated signals in free space are then collected and received by USERs 1 and 2, respectively. At the receiving end, a vector network analyzer (VNA) swiftly collects the signal strength, which is then further demodulated into binary code based on the given transmission frequency, ultimately recovering the two images. The experimental results demonstrate that the proposed SSPP meta-waveguide can facilitate dual-band wireless communications. Compared to communication using metasurfaces, communication based on plasmonic metamaterials boasts a low profile (no need for a spatial excitation) and small size, simplifying integration.

In this research, we have proposed, designed, and experimentally verified a reprogrammable spoof plasmonic meta-waveguide that allows for the flexible manipulation of EM waves in a dual band. Due to the flexibility of the SSPP dispersion behavior, the surface impedance can be controlled by altering the ON/OFF state of the PIN diodes loaded on the SSPP units. Consequently, the SSPP meta-waveguide can be modulated into radiation waves by switching the surface impedance of each SSPP unit in a coding sequence, as demonstrated experimentally. Importantly, we have shown that dual-band wireless communication at 14 and 24 GHz can be realized on an ultrathin planar platform. Compared to other radiators, our scheme offers advantages such as compact size, tunable frequency response, and reprogrammability, while eliminating the need for expensive RF modules and complicated mixing devices commonly used in traditional transmitters (see Appendix E). We believe that our work broadens the scope of spoof plasmonic metamaterials and could find applications in satellite and radar communication systems.

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Supporting information Appendixes A–F. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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