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# Origami-inspired frequency selective surface with large bandwidth modulation range based on electromagnetically induced transparency effect

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Dear editor,

Frequency selective surfaces (FSSs) have been intensively studied as a powerful tool to modulate the transmission of the electromagnetic (EM) waves, allowing either bandpass or bandstop selection of the EM waves [1]. In this study, we periodically deployed the classical resonators for electromagnetically induced transparency (EIT), cut-wire (CW), and split-ring resonators (SRRs), in an origami pattern, which becomes an FSS with ultra-large modulation range based on only a single-layer structure. The FSS's bandwidth can be continuously modulated by the folding process and large bandwidth modulation range of more than 300% can be realized in Ku band by the mechanical deformation of the FSS.

The concept of the FSS is presented in Figure 1(a). Details of the design, simulation and measurement are shown in Appendixes A and B. A CW and a pair of SRR, which act as a classical structure for EIT analogue [2], form the unit cell of FSS and are periodically arranged on the substrate. Slits are cut between the unit cell to define the origami structure. When the compressive strain is applied to the substrate, out-of-plane deformation occurs and the FSS can be folded along the slits. Since the selected structure effectively takes the advantage of the out-of-plane deformation of origami design, the interaction between the resonators can be significantly modulated. The folding and modulation can be realized by either the mechanical loading or the adoption of active materials (e.g., shape memory polymer) with higher switching speeds.

The simulated and measured transmission spectra under TE polarization are shown in Figures 1(b) and (c) with different folding degrees ($\theta$) and angles of incident (AoIs). In the normal incidence condition (AoI $= 0°$), a bandstop behavior with only a dipole resonance peak is observed in Ku band when the FSS is unfolded ($\theta = 0°$). With the increase of folding degree, another resonance peak appears in the higher frequency regime and the bandstop bandwidth of the FSS continuously increases. When the AoI is 30°, the continuously broadening effect of the bandwidth can still be observed with the increasing folding degree. The proposed FSS can maintain good frequency characteristics without any high-order resonance modes until the folding degrees are larger than 45°, as shown in Figure D1 in Appendix D, indicating good characteristics compared with other reported origami-based FSSs [3, 4]. Moreover, we also discussed the transmission properties of the FSS under TM polarization in Figure D2 in Appendix D.

To further illustrate the mechanical modulation effect by the folding of FSS, the dependence of frequency characteristics is plotted in Figure 1(d). At AoI $= 0°$, the appearance of second resonant frequency and its significant blueshift leads to an increase of bandwidth from 0.78 GHz ($\theta = 0°$) to 2.75 GHz ($\theta = 60°$), while the lower resonant frequency remains stable (about 13.95 GHz) during the FSS's deformation. At AoI $= 30°$, in addition to the blueshift of the higher resonant frequency, the lower resonant frequency also has a certain redshift, causing the further broadening of bandwidth (from 0.65 to 2.55 GHz). By defining the modulation range of the FSS's bandwidth as $\frac{\mathrm{BW}_\theta}{\mathrm{BW}_{0°}}$, where $\mathrm{BW}_\theta$ and $\mathrm{BW}_0^\circ$ are the bandwidth of FSS at the folding degree of $\theta$ and 0°, the dependence of modulation range on the folding degree is shown in Figure 1(e). When the folding degree changes from 0° to 60°, the modulation range gradually increases to 350% and 392% with the AoI $= 0°$ and AoI $= 30°$. Compared with other origami-inspired FSS [3–5], our work presents a much larger modulation range with only a single-layer mountain-valley structure, which greatly simplifies the design and the fabrication process.

To understand the reconfiguration mechanism at the occurrence of the folding process, we simulated the surface cur-

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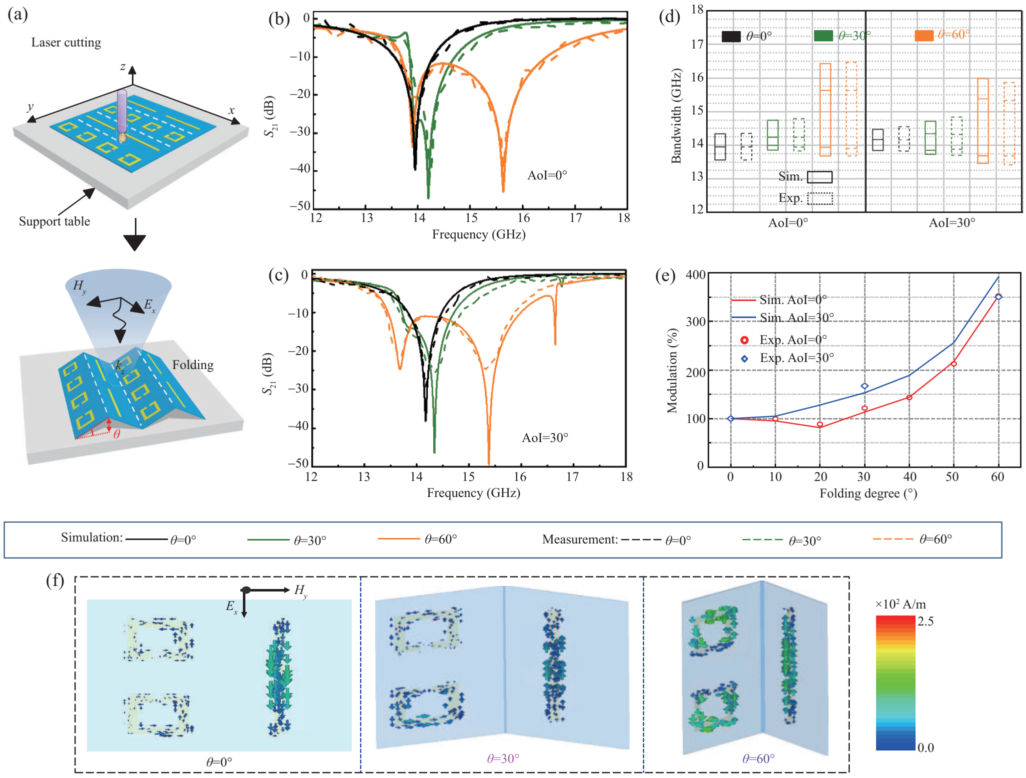


**Figure 1** (Color online) (a) Schematics of the fabrication with two-dimensional precursor and the mechanical reconfiguration process; (b) and (c) are corresponded to the spectral responses of the FSSs with different folding degrees at AoIs of 0° and 30°; (d) the dependence of bandwidth on the folding degree; (e) the dependence of modulation range on the folding degree; (f) the simulated surface current distributions for $\theta = 0°$, $\theta = 30°$, and $\theta = 60°$ (AoI = 0°).

rent density distributions corresponding to $\theta = 0°$, $\theta = 30°$, and $\theta = 60°$, respectively, as shown in Figure 1(f). When the FSS is undeformed ($\theta = 0°$), obvious excitation of CW is indicated by the strong current distributed along the resonator and the same direction of the electric field. As the SRR-pair cannot be directly excited with the gap side perpendicular to the excitation electric field [2], the circulating current in the SRR-pair is very weak. However, with the increase of folding degree, the decreasing coupling distance makes the SRR-pair excite the inductor-capacitor (LC) resonance as the energy of the CW excited by external waves is transferred to the SRR-pair by the electric field coupling. When the coupling distance further decreases, the current distribution indicates more energy is transferred to the SRR-pair, causing the suppression of the electric field in the CW and showing an EIT-like effect similar to previous reports [6]. The strengthening of coupling broadens the bandwidth of the FSS [7], which makes redshift and blueshift of the resonant frequency of SRR-pair and CW respectively.

In this study, we designed and verified an origami-inspired single-layer FSS with a large bandwidth modulation range based on EIT effect. The introduction of EIT structures with a near-field coupling mechanism, showing extraordinary bandwidth modulation characteristics and ultra-large modulation range, will facilitate a novel modulation strategy to FSS's reconfiguration applications.

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**Supporting information** Appendixes A–G 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.

**References**

1 Munk B A. Frequency Selective Surfaces: Theory and Design. Hoboken: John Wiley & Sons, 2005
2 Gu J, Singh R, Liu X, et al. Active control of electromagnetically induced transparency analogue in terahertz metamaterials. Nat Commun, 2012, 3: 1151
3 Fuchi K, Buskohl P R, Bazzan G, et al. Spatial tuning of a RF frequency selective surface through origami. In: Proceedigns of Automatic Target Recognition XXVI, 2016
4 Sessions D, Fuchi K, Pallampati S, et al. Investigation of fold-dependent behavior in an origami-inspired FSS under normal incidence. PIER M, 2018, 63: 131–139
5 Nauroze S A, Tentzeris M M. A thermally actuated fully inkjet-printed origami-inspired multilayer frequency selective surface with continuous-range tunability using polyester-based substrates. IEEE Trans Microw Theor Techn, 2019, 67: 4944–4954
6 Zhang S, Genov D A, Wang Y, et al. Plasmon-induced transparency in metamaterials. Phys Rev Lett, 2008, 101: 047401
7 Su X, Ouyang C, Xu N, et al. Dynamic mode coupling in terahertz metamaterials. Sci Rep, 2015, 5: 10823