the quarter-wavelength fundamental mode by changing the length $\boldsymbol{L_2}$, as shown in Fig. 4(a). In this case, the length $\boldsymbol{L_1}$ is set to be the same in order to fix the half-wavelength resonance frequency. The half-wavelength resonant frequency is therefore almost independent on $\boldsymbol{L_2}$ [red squares, Fig. 4(a)]. Figure 4(a) shows the tunability of the quarter-wavelength fundamental mode, following the guided curve of $\lambda_f = 4\boldsymbol{L_2}$ well [dotted black curve], except for the slight peak position shift due to the strong coupling between the two adjacent resonant modes. In the same way, we realized the tunability of the half-wavelength fundamental mode in the condition of $\boldsymbol{L_2}$ = 270 μm as shown in Fig. 4(b). The tunability characteristics verify that each fundamental mode is independently excited under the corresponding structural parameters: the length $\boldsymbol{L_1}$ of the oblique air-slots for the half-wavelength mode and the length $\boldsymbol{L_2}$ from the crossing position to the end of the center air-slot for the quarter-wavelength mode.

4. Conclusion

In conclusion, we have presented new phenomenon, the quarter-wavelength resonance behavior in planar plasmonic metamaterials consisting of asymmetrically coupled air-slots. Based on the phenomenon, the monopole resonators have been achieved and the tunability of the resonators has been realized by the appreciable variation in geometrical parameters such as the length of air-slots. According to the THz experiments and simulation results, the origin of the quarter-wavelength fundamental mode is associated with the formation of an artificial electromagnetic anti-node at the crossing position of the air-slots and a nodal point at the end of the air-slot. The electromagnetic anti-node appears at the crossing position of air-slots where the strong concentration and oscillation of the electric field occurs due to the effect of the sharp edge of the two tapered metal plates. The planar plasmonic metamaterial structures that generate the quarter-wavelength fundamental mode provide a new method for controlling the light-matter interactions and open the possibility for designing and developing photonic devices that require further size reduction technology.

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