# Effect of swelling of a photoresist on electromagnetic resonance of terahertz metamaterials

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## Abstract

This work uses isopropyl alcohol (IPA) to develop a photoresist. IPA dissolves the photoresist that is not exposed to UV light. The swelling of the photoresist distorts the split-ring resonators (SRRs). The distorted SRRs have a larger loop length, smaller line width, and smaller split gap than undistorted SRRs. The change in the dimensions of the SRRs is caused by the extension of the SRR arms in their longitudinal directions. The resonance frequency of the distorted SRRs is smaller than that of the undistorted SRRs, and the resonance frequency decreases with the development time. The resonance frequency of the distorted SRRs depends on not only their dimensions, but also the bending of their arms. The distorted SRRs in this work have a frequency tuning range with a maximum width of 0.13 THz. The method that is proposed herein uses IPA to fabricate passively tunable terahertz metamaterials, which exhibit the advantages of high reliability, low cost, and ease of fabrication.

## Sample Fabrication

Figure 1 presents the process for fabricating test samples. Identical polyester (PET) substrates with a thickness of 175 μm are used. A 200 nm-thick silver film and a 5 μm-thick PR layer (ENPI202, Everlight Chemical Industrial Co.) are sequentially deposited on each PET substrate. A split-ring resonator (SRR) array on a photomask is transferred onto the PR layers under UV irradiation. After the PR layers have been irradiated with UV, they are baked at 100°C. The baked PR layers are then developed using isopropyl alcohol (IPA) rather than the specific developer of the PR. This development process sets this work apart from previous studies of metamaterials . The test samples have different development times: 45, 90, and 135 min. After they are developed, the test samples are immersed into a metal etchant (E-CHEM Enterprise Co.) to etch the silver layers. The etching time of each sample is approximately 1 s.

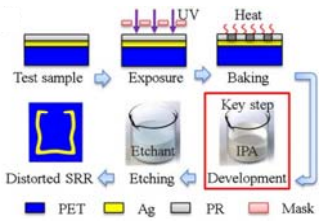


Fig. 1. (a) Fabrication of test samples.

## Experimental SEM

Figures 2(f )–2(h) display the scanning electron microscope (SEM) images of the reference sample, the test sample that was developed for 45 min, and the test sample that was developed for 90 min, respectively. The results in Figs. 2(f )–2(h) reveal that IPA can be used to distort the SRRs in the test samples. The distortion of the SRRs is caused by the swelling of the PR in IPA. A relatively low post-exposure baking (PEB) temperature of 95°C is applied to a test sample to increase the distortion of SRRs. the PR layer that underwent PEB at 95°C and was developed for 45 min is softer than the PR layer that underwent PEB at 100°C and was developed for 90 min.

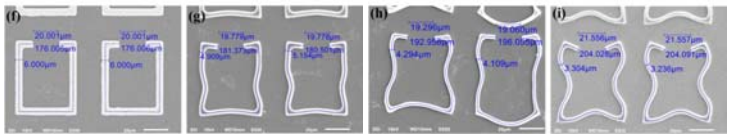


Fig. 2. SEM images of (f ) reference sample, test samples that underwent PEB at 100°C and were developed for (g) 45 and (h) 90 min, and (i) the test sample that underwent PEB at 95°C and was developed for 45 min.

## Experimental Results (I)

Figure 3 presents the terahertz spectra of the reference sample, test samples that underwent PEB at 100°C and were developed for 45, 90, and 135 min, and a test sample that underwent PEB at 95°C and was developed for 45 min. These spectra are obtained using a commercial terahertz spectrometer(TPS 3000, TeraView), and the polarization of normally incident terahertz waves is set parallel to the x axis, as presented in Fig. 1(b). The resonance peak of the reference sample is at 0.65 THz, and the resonance peak of the test sample that underwent PEB at 100°C and was developed for 45 (90) min is at 0.63 (0.57) THz. This result depicts that the resonance peak of the test sample that was developed for 45 (90) min is redshifted by 0.02 (0.08) THz. The redshifts of the spectra of the test samples arise from the increase in the loop length of the SRRs , the decrease in their line width , and the decrease in their split gap. This result reveals that a test sample reaches its minimum resonance frequency as it is developed for a particular development time. Therefore, a development time of 90 min yields a larger frequency tuning range than development times of 45 and 135 min at a PEB temperature of 100°C. The resonance frequency (0.52 THz) of the test sample that underwent PEB at 95°C is redshifted from that (0.65 THz) of the reference sample, as displayed in Fig. 3. Therefore, this test sample has a frequency tuning range with a maximum width of 0.13 THz herein. The distorted SRRs can be used to develop passively tunable terahertz devices such as filters, absorbers, sensors, and spectral imagers.

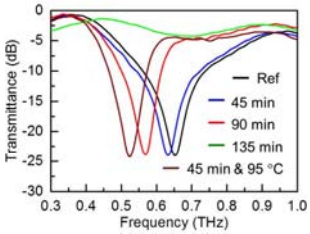


Fig. 3. Experimental spectra of the reference sample, test samples that underwent PEB at 100°C and were developed for 45, 90, and 135 min, and test sample that underwent PEB at 95°C and was developed for 45 min.

## Experimental Results (II)

**A simulation is performed using computer simulation technology (CST) software to verify the dependence of the resonance spectra on the dimensions of the distorted SRRs. As the arms of the distorted SRRs are bent, the consequent shift of the resonance spectrum is caused not only by the asymmetric electrical coupling but also by the change in the areas that are enclosed by the distorted SRRs. The electromagnetic resonance of an SRR can be treated as a simple inductance capacitance resonance. The resonance frequency (f) of the SRR is given by the equation $f = 1/2\pi\sqrt{LC}$, where C is the capacitance of the split gap of the SRR, and L is the inductance of the loop of the SRR and is directly proportional to the area that is enclosed by it. The equation reveals that the outward (inward) bending of the arms of an SRR increases (reduces) the enclosed area, increasing (reducing) its inductance, resulting in a redshift (blueshift) of its resonance spectrum. Accordingly, both the asymmetric electrical coupling and the change in the enclosed area shift the resonance spectrum of the distorted SRRs as their arms bend.**

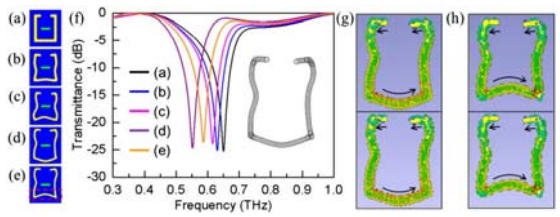


Fig. 4. Simulated units of (a) the reference sample and (b) the test sample that underwent PEB at 100°C and was developed for 45 min. (c) and (d) Simulated units of the test sample that underwent PEB at 100°C and was developed for 90 min. (e) Simulated unit with the same dimensions as that in (d) but with its bottom arm (inside a red dashed frame) bent inward toward the geometrical center of the simulated unit. (f ) Simulated spectra of SRR arrays, each of which comprises one of five simulated units. The inset presents a simulated unit constructed from small circular disks. (g) Current flow distribution of the SRR array that comprises the SRR unit in (d). (h) Current flow distribution of the SRR array that comprises the SRR unit in (e).

## Conclusion

- the distorted SRRs are fabricated by the swelling of a PR in IPA during its development.
- The resonance spectrum of the distorted SRRs is redshifted from that of undistorted SRRs, and the spectral redshift increases with the development time.
- The simulated results reveal that the resonance frequency of the distorted SRRs depends not only on their dimensions, but also the bending of their arms.
- The distorted SRRs in this work have a frequency tuning range with a maximum width of 0.13 THz. Therefore, the distorted SRRs can be used to develop passively tunable terahertz metamaterials.

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## References

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