Mutual coupling effects between meta-atoms for enhanced bandwidth

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Abstract We analyzed theoretically and experimentally the inter-element coupling behavior between the periodic structure's so-called "meta-atoms" by varying the number of meta-atoms arranged periodically in the array. For this reason a planar metamaterial consisting of ring-shaped subwavelength periodic structures on a thin metal film was developed to exhibits a resonant transparency at the frequency of about 0.35 THz. The cross-talk between the meta-atoms due to electromagnetic multipole interferences lead to a significant change in resonance bandwidth and the quality (Q) factor. We anticipate that found coupling behavior between inter-element with subwavelength dimensions can potentially be used for a variety of applications such as filters, multi-pixel emitter and detector arrays, etc. for broad THz frequencies.

Resonator modelling

The schematic representation of a single resonator is shown on the left-hand side in Fig.1. The initial dimensions of a single resonator were set to a radius of circular rings R1, R2 and R3 with 250, 170 and 96 microns, respectively. The width of metal bar connected through the circular rings was W=42 µm, and the lattice periods along X and Y directions were fixed with $P_x = P_y = 650$ µm. Microscope image of sample composed of 5x5 array of meta-atoms fabricated by the direct laser ablation technique (DLA) is shown on right-hand side in Fig.1.

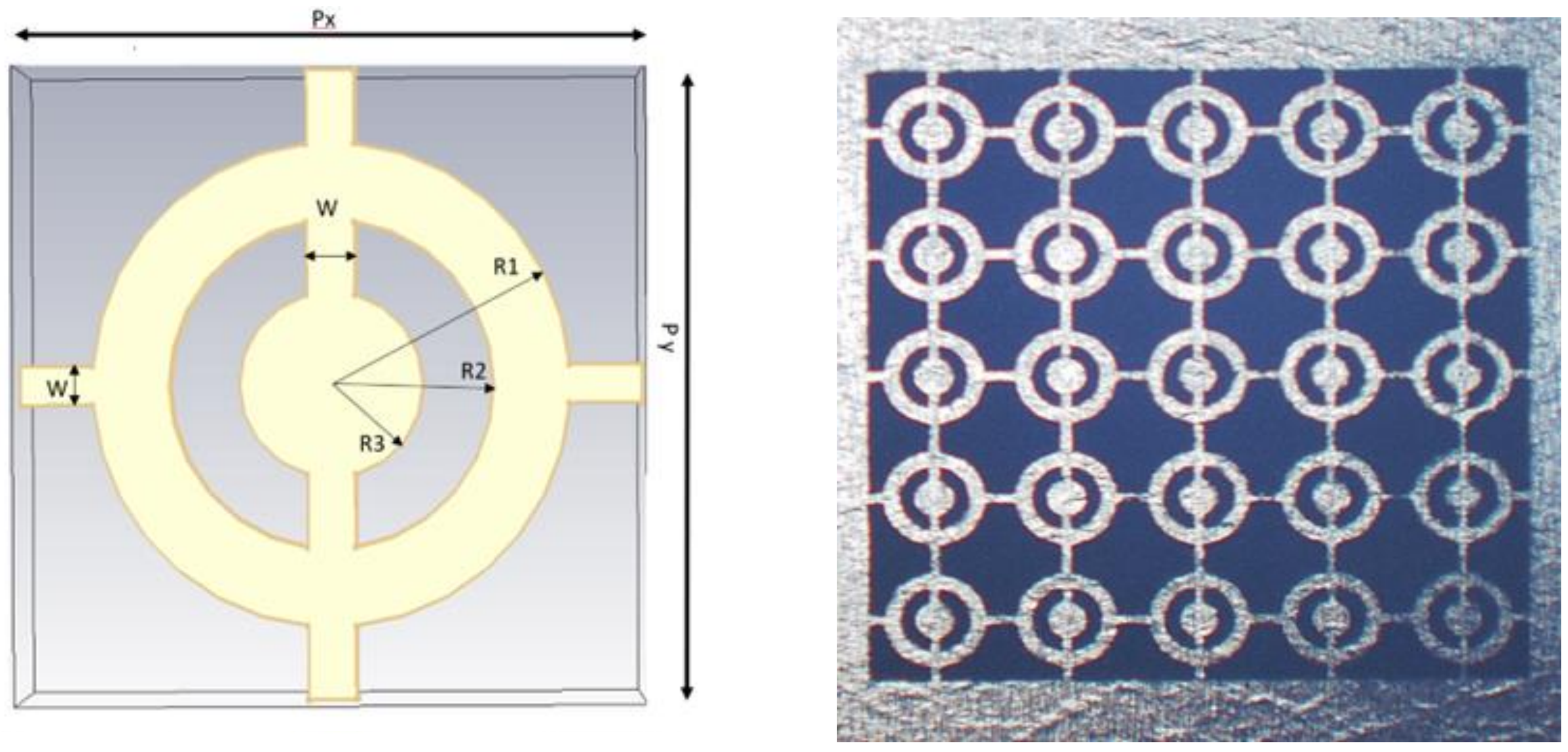

Fig.1. (left-hand side) Drawings of single meta-atom in a frame. (right-hand side) Microscope image of fabricated 5x5 array of meta-atoms a frame of 50-µm-thick stainless steel film.

Experimental Validation

The below figures shows the FDTD simulation results and THz-TDS experimental findings of transmission spectra of sample consists of meta-atoms periodically arranged in 5x5 array and 1x1 array. Resonant peak is found at around 0.35 THz frequency. We can see the peak broadening for 5x5 array sample compared to the single meta-atom in a frame. The enhanced behaviour of bandwidth can be attributed to the mutual coupling occurring between multiple meta-atoms arranged in the array.

Amount of meta-atoms	Bandwidth (Δ*f*) Sim/Exp	Peak frequency (*f*) Sim/Exp	Q-factor (*f*/Δ*f*) Sim/Exp
1 (single element)	46GHz/71GHz	350GHz/340GHz	7.6/4.8
4 (2x2 array)	159GHz/148GHz	361GHz/360GHz	2.3/2.4
25 (5x5 array)	160GHz/172GHz	345GHz/350GHz	2.1/2.0
100 (10x10 array)	175GHz/184GHz	346GHz/340GHz	1.9/1.8

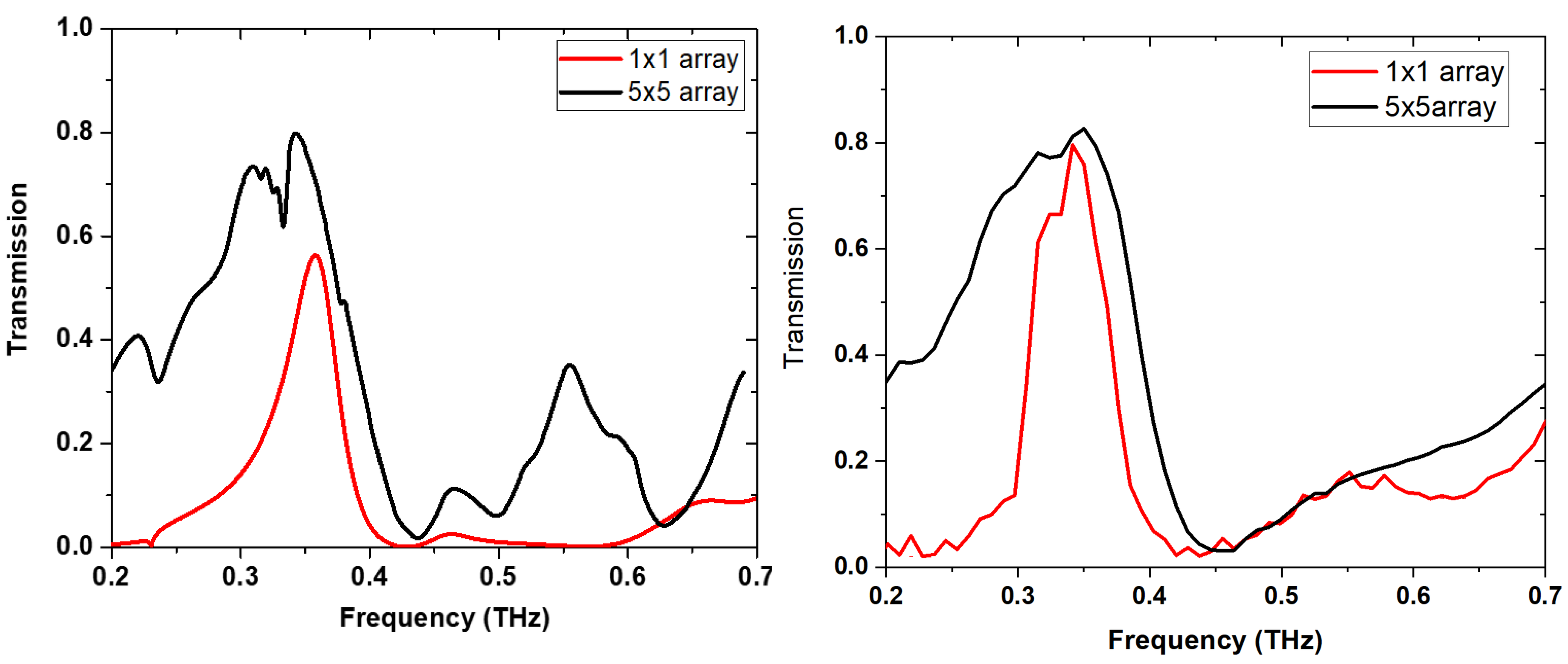

Fig.3: (left-hand side) FDTD simulations and (right-hand side) THz-TDS measurements. of the transmission spectra at TM polarization of the sample composed of 5x5 array (black color) and single (red color) meta-atom in a frame. The change in Q-factor was shown in Table

Characterization Methods

Simulations are carried out using a normal illumination of electromagnetic wave by choosing a perfectly matched layer (PML) boundary conditions so that waves can pass through with minimal reflections from the structure. The S-parameter calculations were performed for both TE and TM polarizations assuming the steady-state energy criterion using a multi-frequency plane wave onto the sample.

The samples were characterized using a commercial THz-TDS system (TeraVil T-SPEC 800) in the frequency range of 0.1–2.0 THz at a room temperature. The output of a femtosecond laser pulse is split into two beams using a beam splitter (BS). One beam is used to generate THz radiation, modulated with frequency (f) and other beam is routed through a delay line and used to detect the THz beam. The THz pulses emitted out from a THz emitter was transmitted through the empty aperture (reference) and resonators with aperture (sample) which then collected through the THz detector. As the, electric field is measured in the time domain the Fourier transform of these time pulses yields the spectral information.

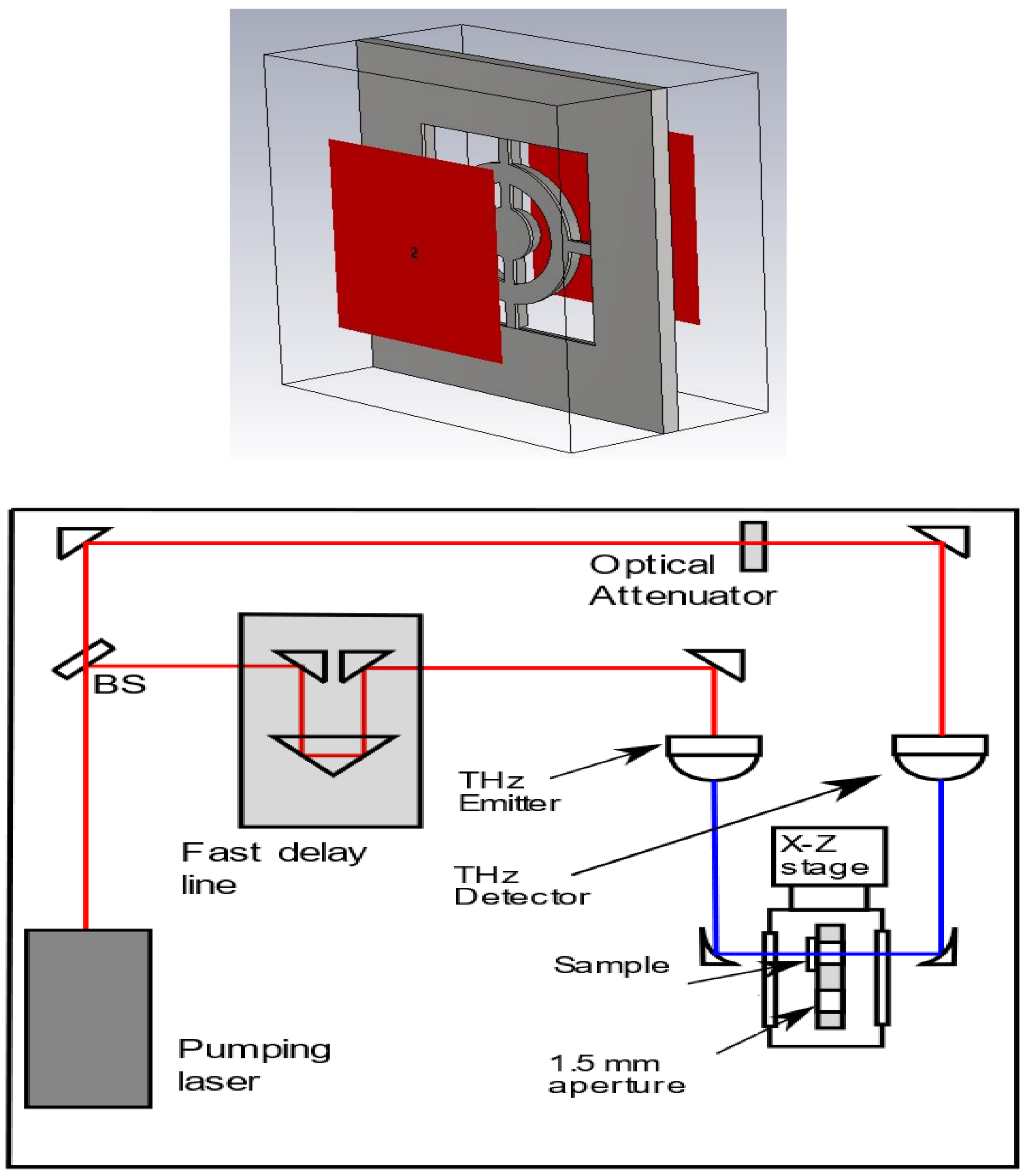

Fig.2. Illustrates methods used to characterize the samples. (top) FDTD simulation window and (bottom line) experimental setup of THz-TDS. D. Pashnev, *Appl. Phys. Lett.* **117**, 051105 (2020)

Conclusions and Future work

In conclusion, we have designed and developed the samples with different number of meta-atoms: from single meta-atom up to 10x10 array of meta-atoms in a frame. Both simulated and experimental transmission characteristics showed a clear resonant feature at TM polarization centered at the frequency of 0.35 THz. Peak broadening due to inter-elemental coupling was observed with the change of bandwidth and the quality factor values from 46/71 GHz to 175/184 GHz and from 7.6/4.8 to 1.9/1.8 in the modeling/experiment, respectively.

Further work, we will investigate existence of multipole expansions (such as toroidal dipoles and quadrupoles) and understanding the mutual coupling behavior between each subwavelength meta-atom which lead to deterioration of spectral quality. A clear study of such inter-element coupling behavior between meta-atoms can potentially lead to development of huge variety of photonic devices for broad range of frequencies.

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