Design of a THz-MEMS Frequency Selective Surface for Structural Health Monitoring

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Abstract— This paper characterizes the relationship between applied force and reflectance/ transmittance of a terahertz frequency selective surface for use as a sensor in structural health monitoring. Numerical modelling of both the mechanical and electromagnetics, solving the elasticity equation and Maxwell's equations, respectively, has been undertaken for a 3 layer device. The unit cell comprises of a metal cross wire embedded within a (hard) silicon substrate, interleaved with stacks of (soft) low density polyethylene.

Structural health monitoring (SHM) is an important multidisciplinary topic in engineering which can benefit from emerging terahertz (THz) and microelectromechanical systems (MEMS) [1]. Frequency selective surfaces (FSSs) can also be used with THz-MEMS, as demonstrated in a polarization modulator [2]. Here we combine THz-MEMS with a FSS architecture to create a passive sensor that can be discretely integrated into the (sub)surface of structures, without impeding its functionality. We present a study of both the electromagnetic [3] and mechanical design of a THz-MEMS FSS stress sensor, operating at 668.5 GHz.
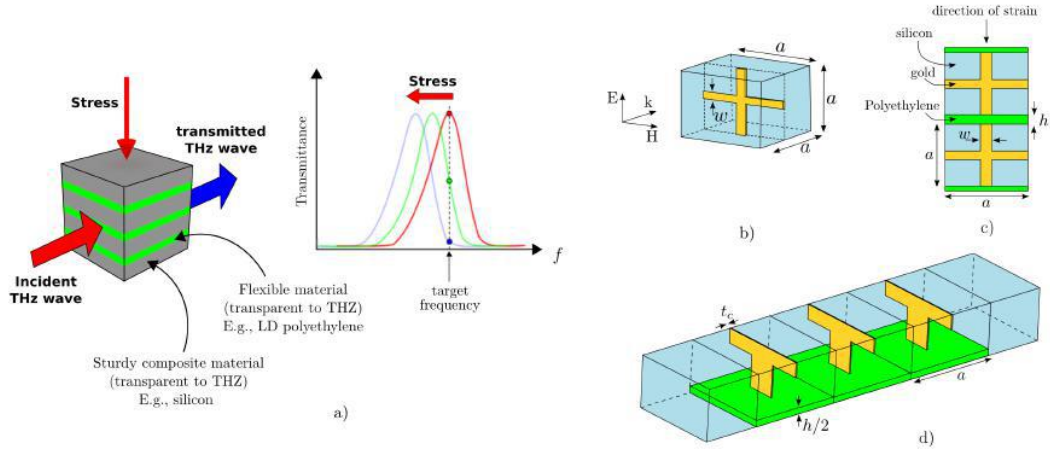

Figure 1: Illustrations of a) overview of working principle, b) a unit cell of the cross wire FSS structure, c) how cells are stacked between layers of LDPE to build the FSS structure, and d) the 3-layer reduced model used in the electromagnetic simulations.

Figure 1(a) represents a conceptual illustration of the device and overview of its operating principle. The device comprises of stacks of hard and soft materials that when compressed cause a shift in the frequency response. To achieve this, a FSS is embedded within the hard material. When compressed, the element spacing of the FSS is reduced, causing the required frequency shift, resulting in a decrease in transmittance at the operating frequency. Figure 1(b-d) shows the unit cell, geometry and materials of the THz-MEMS FSS structure. An operating frequency of 668.5 GHz was chosen as this is the absorption minimum in the window of interest of 500-700 GHz [4]. Through optimization, the following parameters were determined: lattice parameter $a = 47.45~\mu$m, wire width $w = 14.75~\mu$m, wire thickness $t_c = 500$ nm and the Low Density Polyethylene (LDPE) layers have a thickness $h = 12.7~\mu$m (0.50 mil) when no external force is applied.

Figure 2(a) and 2(b) show the numerical results for the reflectance and transmittance, respectively, of the 3-layer stack FSS as it is compressed. The optimization curve is a maximum at the optimum operating frequency, where the maximum dynamic range between compressed and uncompressed states is found.
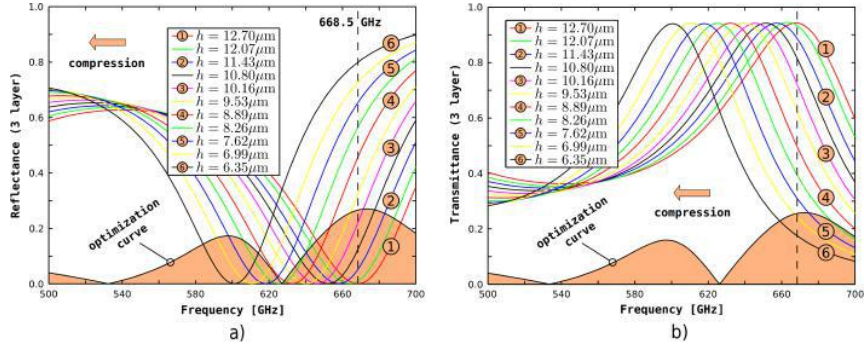

Figure 2: a) Reflectance, and b) transmittance of the 3-layer THz sensor.

Mechanical simulations of the device were undertaken to calculate the force required to displace the sensor. Figure 3a) shows the simulated mesh and mechanical displacement when a force of 100 μN is applied to the top and bottom of the structure. Figure 3(b) demonstrates the change in reflectance and transmittance for a 3-layer structure at 668.5 GHz, when different forces are applied. By changing the soft material, under compression, the range of applied forces at which the sensor operates can also be optimized.
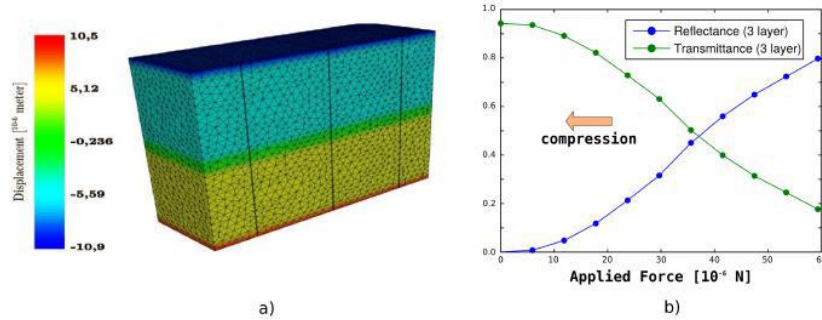

Figure 3: Mechanical analysis of the FSS: a) mesh and displacement data from a FEM simulation of the elasticity equation, and b) reflectance and transmittance as a function of applied force.

In conclusion, rigorous computational analysis has been presented of a THz-MEMS FSS for use as a stress sensor, having several applications in SHM. In particular we have described a method to determine the reflectance and transmittance as a function of applied force, which can be easily adapted to the design of other structures.

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