MEMS Orientational Optomechanical Media for Microwave Nonlinear Applications

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***Abstract*— The fabrication and testing of orientational optomechanical media suitable for microwave phase conjugation is described. It consists of metal-coated dielectric elongated beams 1 mm $\times$ 100 μm $\times$ 10 μm suspended by nonconductive torsional springs attached to a microwave transparent frame. Rotation of single elements, in a polarized electromagnetic field at 15 GHz, was measured and found to be in a good agreement with theory. This first experimental implementation of using microelectromechanical structures (MEMS) for nonlinear microwave devices demonstrates the potential of an entirely new class of devices.**

I. Introduction

PHASE CONJUGATION at microwave frequencies has attracted much attention in recent years [1]–[3]. Optical birefringence [2] and phase conjugation via degenerate four-wave mixing (DFWM) [3] using a mineral oil–heptane suspension of shaped carbon microfibers at centimeter wavelength has been demonstrated. To obtain a number of practical advantages over liquid suspensions of shaped microparticles for device applications, a new class of artificial dielectric media was suggested [1], [4]. These media consist of three-dimensional (3-D) arrays of electrically small, anisotropic particles that are mechanically supported and free to rotate, under the action of electromagnetically induced torques, into preferred directions set by the net polarization vector of the incident radiation. Rotation of the particles changes the effective index of refraction of the medium and gives rise to orientational index gratings that can be used for active optical processes. These particle arrays are referred to as orientational optomechanical media and have unique dielectric and dynamic properties such as reasonable optical response times, overall thermal, optical, and mechanical stability, and control. They are therefore an unusually promising microelectromechanical structures (MEMS) candidate for active optical applications at microwave and millimeter frequencies.

In this letter, we report fabrication and testing of the first prototype of an optomechanical medium consisted of 1 mm $\times$ 100 μm $\times$ 10 μm polyimide beams covered with 0.2 μm of aluminum and supported by two nonconductive torsional springs attached to a 10-μm-thick dielectric frame. Our MEMS device demonstration combines the micromachining fabrication techniques with the concept of active millimeter-wave nonlinear devices. As a next step, microwave phase conjugation via DFWM in 3-D arrays of mechanically supported metal-coated rods will be measured.

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II. Design and Fabrication

A particle with polarizability tensor $\alpha(\hat{\Omega})$, where $\hat{\Omega} \equiv (\theta, \phi)$ are the orientational angles of its symmetry axis, in the electromagnetic field $\vec{E}(\vec{r}, t)$ acquires a dipole moment $\vec{p} = \alpha(\hat{\Omega}) \cdot \vec{E}$. This then couples back to the radiation field giving rise to an electrostrictive potential $U(\vec{r}, \hat{\Omega}; t)$. Associated with $U(\vec{r}, \hat{\Omega}; t)$ is electrostrictive force $\vec{F}(\vec{r}, \hat{\Omega}; t)$ and electrostrictive torque $\vec{\Gamma}(\vec{r}, \hat{\Omega}; t)$. If the particles are fixed in space, we can neglect electrostrictive forces that tend to change the particles' density distribution. The maximum field induced torque can be expressed as $|\vec{\Gamma}| = (4\pi/c)\beta I$, where β is the asymmetric component of particle polarizability, I is the field intensity, and c is the speed of light. Nonabsorbing, symmetrical microellipsoids are characterized by polarizability components α_{ll} parallel to the symmetry axis and $\alpha_{\perp}$ in any direction perpendicular to this axis. It can be shown that the asymmetric polarizability β can be expressed in terms of the components of the tensor $\alpha(\hat{\Omega})$

$$\alpha_{ll} = \frac{V}{4\pi} \frac{\varepsilon - 1}{1 + \frac{3}{8\pi}(\varepsilon - 1)A_1(a, b)}$$

and

$$\alpha_{\perp} = \frac{V}{4\pi} \frac{\varepsilon - 1}{1 + \frac{3}{8\pi}(\varepsilon - 1)A_2(a, b)}$$

where V is the ellipsoid's volume, ε is the dielectric constant, and A_1 and A_2 are depolarization coefficients [5].

For metal or metal-coated ellipsoids, the asymmetric component of the particle's polarizability is

$$\beta = \alpha_{ll} - \alpha_{\perp} = abc\left(\frac{1}{A_1} - \frac{1}{A_2}\right)$$

where a, b, c are the major ellipsoid semiaxises. Field-induced torques can therefore be optimized choosing appropriate shaped ellipsoid particles. For fabricated beams of dimensions 1 mm $\times$ 100 μm $\times$ 10 μm the calculated asymmetric component of polarizability was $\beta = 4.68 \times 10^{-5}$ cm^{-3}.

For an optomechanical medium composed of an array of spring-supported beams, we must take into account the twisting torque that the springs generate as the beams rotate. The torque Γ_S is given by $\Gamma_S = (J_S G/L)\Delta$, where J_S is the polar moment of inertia of the spring with the length L, and spring shear modulus G with Δ the angle of rotation.

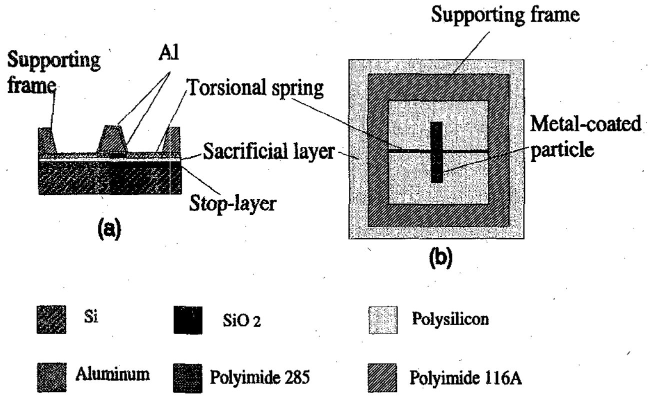

Fig. 1. (a) Cross section and (b) top views of a single rotating element fabricated by standard micromachining techniques.

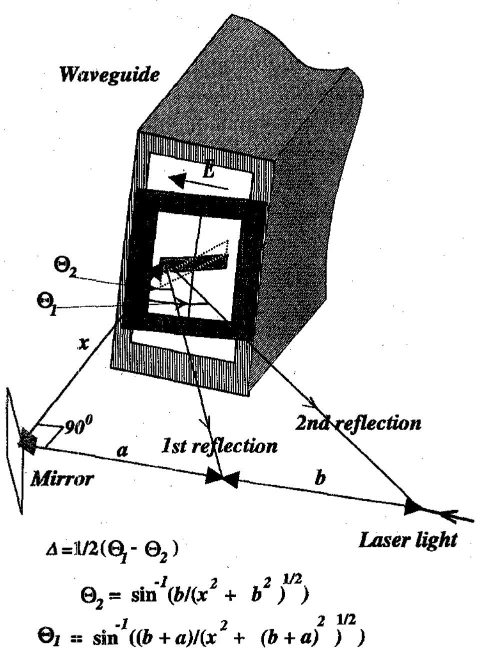

Fig. 2. Optical part of experimental setup for measurement of interaction of optomechanical medium with microwave radiation.

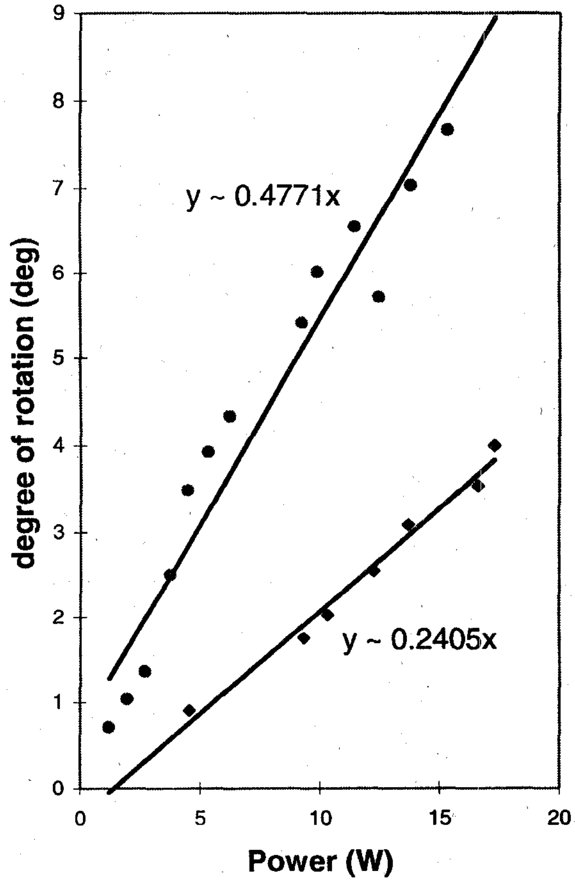

Fig. 3. Degree of rotation of two metal-coated dielectric beams each suspended by two torsional springs with the width of 4 μm (top line) and 7 μm (lower line), respectively. Solid lines are least square approximation for linear dependence $\Delta(P)$.

Assuming field-induced torques of about 10^{-13} Nm and a desired rotation of 90°, this requires torsional spring constant $k = \Gamma_S/\Delta$ of approximately 6×10^{-15} Nm deg^{-1}. Such a small spring constant eliminates from consideration such attractive fabrication materials as polysilicon and SiO_2. We consequently chose polyimide for our applications because of its low shear modulus ~1 GPa and relative ease of processing. Moreover, it allows us to fabricate nonconducting springs and supporting frames of sufficiently different thicknesses using commercially available Probimide 100 and 200 series. Fig. 1 shows a cross section and a top view of a single rotating element. Two by two square inch arrays with 100 equally spaced elements were fabricated on the top of 4-in. silicon wafer with a sacrificial polysilicon layer and low temperature oxide used as a stop layer with standard photolithography techniques. To release the fabricated structures xenon difluoride (XeF_2), a dry isotropic etchant [6] was used to circumvent the liquid surface tension forces present during conventional wet etching. Finally, fabricated structures were glued to a Rexolite frame, which later will allow for 3-D stacking. As a result, we fabricated arrays of dielectric beams covered with aluminum with dimensions 1 mm $\times$ 100 μm $\times$ 10 μm each supported by 1-mm-long, 0.6-μm-thick torsional springs. To vary the spring constant k as well as its mechanical strength, springs with widths between 4 μm and 10 μm were fabricated. The torsional spring constant of the most compliant spring was calculated to be 1.5×10^{-13} Nm deg^{-1}.

III. Measurements

In our first experiments the response of fabricated arrays of mechanically suspended metal-coated particles to microwave radiation at 15 GHz was measured. A TWT amplifier with output power up to 20 W in Ku-band was used to illuminate the rotating elements. The light of a He-Ne laser was focused to a spot size less than 100 μm on the side of a particle, and the reflection was directly observed with a video camera. The optical part of the setup (Fig. 2) allowed for the measurements of the rotation of a single element resulting from electrostrictive torques produced by the interaction of the orienting beam with electromagnetic radiation.

Fig. 3 shows the measured degree of rotation of 1 mm $\times$ 100 μm $\times$ 10 μm aluminum coated dielectric beam suspended by two torsional polyimide springs. The width of the strings was 4 μm and 7 μm, respectively. Elements were placed very close to the edge of the microwave waveguide to maximize the intensity of the field. The intensity is assumed to be $I = P/S$, where P is measured output power and S is cross-sectional area of the waveguide. The rotation of the beam versus intensity of the electromagnetic field is linear. We observed no hysteresis in the beam's rotation with several consecutive changes in the field magnitude. The ratio of the measured two spring constants is $k_1/k_2 \approx 1.98$, which is fairly close to theoretical (geometry based) value of 1.87. The experimental value of a spring constant for 4-μm- and 7-μm-wide torsional springs was found to be 3.28×10^{-14} Nm deg^{-1} and 6.51×10^{-14} Nm deg^{-1}, respectively, which are four times less than our theoretically calculated values. This fact reflects an underestimate of the asymmetric part of beams polarizability. In our calculations we assumed them to be of the shape of the ellipsoid of revolution whose volume is almost one half of the actual volume of the fabricated parallelepiped beams of the dimension $2a \times 2b \times 2c$.

IV. Conclusion

Two-dimensional arrays of elongated metal-coated dielectric rods each supported by nonconductive torsional springs were fabricated by micromachining techniques. Rotation of the beams induced by microwave irradiation at 15 GHz was found to be in a good agreement with theoretical calculations of the response of such optomechanical medium to electromagnetic radiation. This is the first implementation of previously suggested orientational optomechanical media. This demonstrates the feasibility of a MEMS approach, the use of microelectromechanical structures, to generate an entirely new class of nonlinear microwave and millimeter-wave devices. A stacked 3-D array is now being constructed for use at Ku-band. As a next step, fabricated arrays will be used in phase conjugation experiments via degenerate four-wave mixing.

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