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Optomechanical beam steering by surface plasmon nanoantenna

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ABSTRACT

Controlling the far field pattern of the electromagnetic (EM) waves has many applications including wireless communications, radar detection, and industrial applications. The dynamic control of EM patterns is called beam steering. Despite advantages in each technique, the speed, angular range, and spectral range of beam steering is limited due to mechanical and optical properties of such systems. Here we present a beam steering method by means of an array of optomechanical nanoantennas in which the generated optical force of each antenna results in changes to the antenna response due to mechanical reconfiguration. As a result, the antenna far field phase is changed due to the mechanical movement generated by the optical force. Depending on the mechanical properties of the movable component of the antenna, the phase of the antenna can be tailored for a given optical source power. FDTD simulations are used to calculate the optical response of antenna. A phase array of optomechanical nanoantennas is used to do beam steering. The main far field lobe is steered by 0.5 degrees as a result of the mechanical reconfiguration of the phased array.

1. INTRODUCTION

Surface plasmons (SP) are collective motions of electrons generated at the interface between two mediums of opposite signs of dielectric susceptibility (e.g. metal and dielectric) by incoming light waves [1]. SPs have recently been used applications for enhanced optical transmission [2, 3] and biosensing [4-6]. Recently, SP based devices have been used for all-optical modulation [7-11]. More significantly, opto-mechanical coupling has been used for optical modulation and tuning [12-14], optical switching [11], photodetection [15, 16], and optical gradient force sensing and manipulation [17-19]. Here, we present a method for controlling the shape and direction of an electromagnetic (EM) wave in the far field using SP based optical force method.

Controlling the shape and direction of EM wave in the far field region has many applications including free space optical communication [20], optical interconnections [21], data storage [22], laser and projection displays [23], obstacle avoidance systems [24], and laser micromachining. Beam steering can also be considered as a novel approach to reduce high power consumption in wireless communications. The current technologies to steer laser beam precisely to a specific location include mechanically controlled mirrors [25], opto-micro-electro-mechanical systems (MEMS) [26], acousto-optic modulators [27], and liquid crystal electro-optic systems [28]. Despite advantages in each technique, the speed, angular range, and spectral range of beam steering is limited due to the mechanical and optical properties of such systems. Although for radio and microwave frequencies, there are well established methods for beam forming of a transmitter, for infrared and optical frequencies, challenges remain. The main difference of optical antenna – a transmitter /receiver at the region of infrared and optical spectrum – with radio frequency (RF) and microwave antenna is the metal dispersion characteristics. Perfect conductor is a fair assumption at RF and microwave regions as the plasma frequency of metal is far away from the operating frequency of the antenna. However, in infrared/optical frequencies, the variation of the metal's permittivity as a function of frequency should take into account the fact that for smaller wavelengths, higher loss is produced in the antenna. In addition, metal's skin depth is nontrivial compared with antenna dimensions. Besides the physical difference, fabrication of optical antennas is much more difficult than RF and microwave antennas. While the resonance lengths of antennas is on the order of free space EM wavelength in the RF and microwave spectrums, for optical antennas it is much smaller than optical wavelengths due to the fact that light can be

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squeezed by surface plasmon (SP) into deep subwavelength scale (on the order of micron/submicron). Thus, optical antenna fabrication needs sophisticated photolithography, e-beam lithography and ion milling to achieve micron/submicron features. Since beam steering needs dynamic control over the phase of the antenna, the antenna should be tunable by an external signal. There are many ways to imposing tenability of the antenna such as loading the antenna with an optical/electrical controllable material, or an optical/electrical reconfigurable component. Although the former has more superiority in speed and energy consumption, a lot of complexity and difficulty come along often in designing and fabrication due to introducing semiconductor material at the specific region of antenna which demands sophisticated lithography. However, controlling antenna response by reshaping does not need any material deposition and post lithography and as a result, the fabrication will be easier and cheaper. In our previous work, we presented optomechanical nanoantenna as a new class of antenna which the generated near field optical force can reconfigure the antenna mechanically to change antenna scattering properties. Since the near field is focused into deep subwavelength region the optical force, which is proportional to the gradient of the EM energy, can be considerable. The notion of incorporating optical force with the antenna can represent a powerful tool to impose tunability to the antenna without adding further complexity. Since in optical and infrared frequencies, the size of the antenna is much smaller than the operating wavelength due to SP light confinement, higher mechanical bandwidth and smaller switching energy are achievable compared with the conventional optomechanical devices as the mechanical bandwidth is inversely proportional to the antenna's characteristic length. Besides, reconfiguration of a component can be considered as a dramatic change in electric permittivity at the place of that component providing considerable depth of modulation and on/off ratio in optomechanical based modulators and switches.

In RF and microwave antenna, the basic idea to shaping a beam is to manipulate the phase of antenna radiation because an array of antenna with different phase can produce a phase front with defined pattern [29]. In fact, in RF and microwave, all the antennas in the array have the same far field response and phase shift is mainly controlled by imposing a delay to the feeding current or arranging antennas in space such that a phase shift is generated due to their spatial distance with respect to each other. The phase shift in current can be manifested in electric and magnetic field phase depending on the antenna type. Figure 1 shows the schematic of phased array antennas.

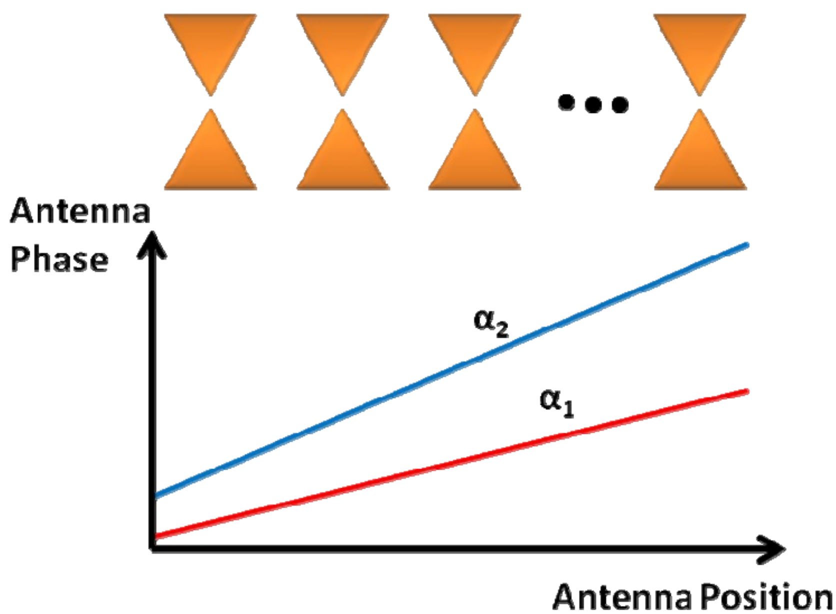

Figure 1 Phased array antenna. The graphs bellow the schematic shows two different phase shift α_1 and α_2 between antennas which is shown as Bowtie antenna

For example, an array of N antennas with equal spacing *d* and having progressive phase α with respect to each other can produce far field pattern as follows [30]:

$$E = \sum_{n=0}^{N} |E_n| e^{-in\alpha} e^{iknd\cos\theta} = \sum_{n=0}^{N} |E_n| e^{in(kd\cos\theta-\alpha)} \sim |E_0| \sum_{n=0}^{N} e^{in(kd\cos\theta-\alpha)}$$

where, $A(\theta) = \sum_{n=0}^{N} e^{in(kd\cos\theta-\alpha)}$ is array factor. The far field pattern of an array of antenna, therefore, is the product of single antenna pattern and array factor which is a quantity determined by phase shift and spacing of antennas. Now the main lobe is located at $\theta = \cos^{-1}\left(\frac{\alpha}{kd}\right)$. As a result, the main lobe of antenna can be steered by dynamically changing the phase shift α.

In infrared and optical frequencies, it would be difficult if not impossible to adjust the phase of optical source corresponding to each antenna in an array due to the fact that the optical/infrared source is usually quantum emitters such as an electron in a laser cavity. As a result, delay lines by means of resonators are used to have phase delay in the antenna feed which can increase the complexity and power loss of the system. Although spatially arrangement of antennas can produce phase at the far field, it cannot provide tunability by itself. In fact, source phase shift together with spatial phase shift of antenna could be dynamically control the beam by controlling the former.

It is clear that by dynamically changing α, the main lobe position will be changed. In conclusion, in order to dynamically change the pattern of the antenna for optical/infrared frequency, one needs to control the phase of far field response of the antenna. As mentioned before, optomechanical control of antenna can be considered as one of the easiest way to adjust and tune the antenna response.

Here we present beam steering by means of an array of optomechanical nanoantennae in which the generated optical force of each antenna can result in change the antenna response due to mechanical reconfiguration. As a result, the antenna far field phase can be changed due to mechanical movement generated by optical force. Depending on the mechanical properties of movable component of the antenna, phase of antenna can be tailored for a given optical source power. For example, if the movable part is bended by exerting optical force, the length and cross section of movable part of the antenna determines the amount of deflection and as a result the mechanical induced phase shift. Since EM field is usually propagating along antenna, the resonance response of antenna is more sensitive to the lengths of antenna components than their cross sections. For beam steering applications, the antenna phase response should be dynamically controlled without degradation of amplitude response. As a result, changing the cross section is more reliable than changing the length. Regarding fabrication concerns, adjusting phase of antenna by changing the width of the component is easier than changing its thickness.

2. OPTOMECHANICAL NANOANTENNA ARRAY

The optomechanical nanoantenna using in beam steering is composed of bowtie antenna whose arms are attached to suspended beams as shown in figure 2. Since bowtie antennas can couple far field into focused near field, electric field is enhanced at the gaps between suspended beams. Considerable optical force can be generated as a result of EM energy confinement. The optical force is attractive and bends the two beams across each gap toward each other resulting in change of antenna response.

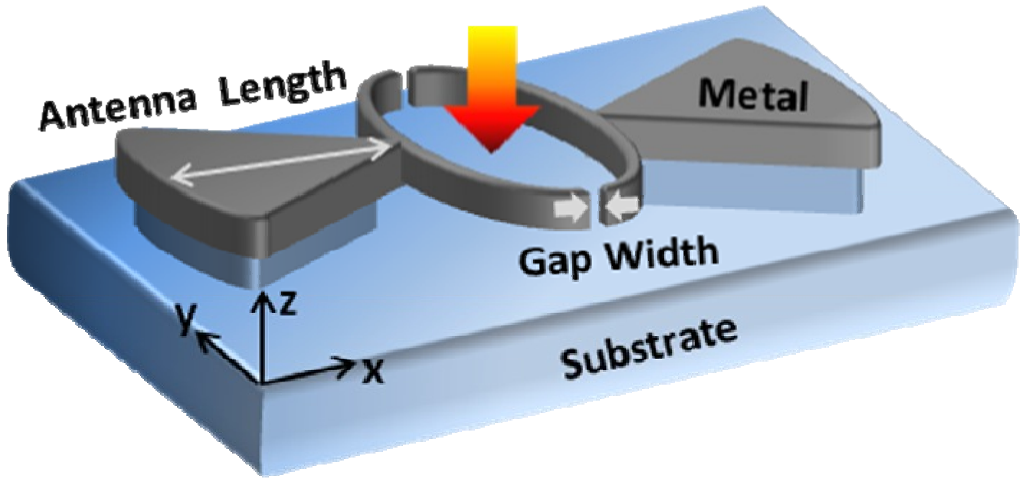

Figure 2 Schematic of optomechanical nanoantenna used to steer beam. A plane wave is assumed to shine the antenna at top and results in strong confinement at the gap regions.

3. SIMULATION

The FDTD simulation is used to calculate the optical response of antenna. By gathering electric and magnetic fields around each beam, optical force on each beam can be calculated. By coupling the optical response and mechanical response of the antenna, we can calculate the gap width of antenna as a function of optical force. The full procedure can be found in [11]. Figure 3 shows the final gap width as a function of initial gap width and optical power. Far field amplitude and phase of the near field of antenna are calculated and the variation of these quantities as a function of the initial gap width and optical power is shown in figure 4.

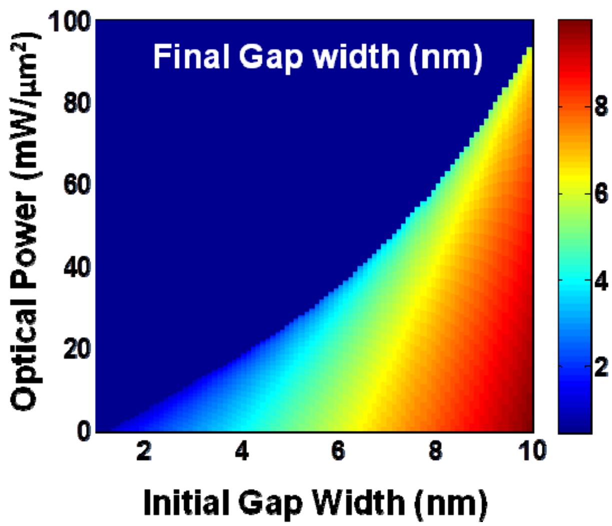

Figure 3 Gap width between the beams attached to arms of Bowtie antenna. By Applying optical power, beams are deflected toward each other and as a results the gap width decreases.

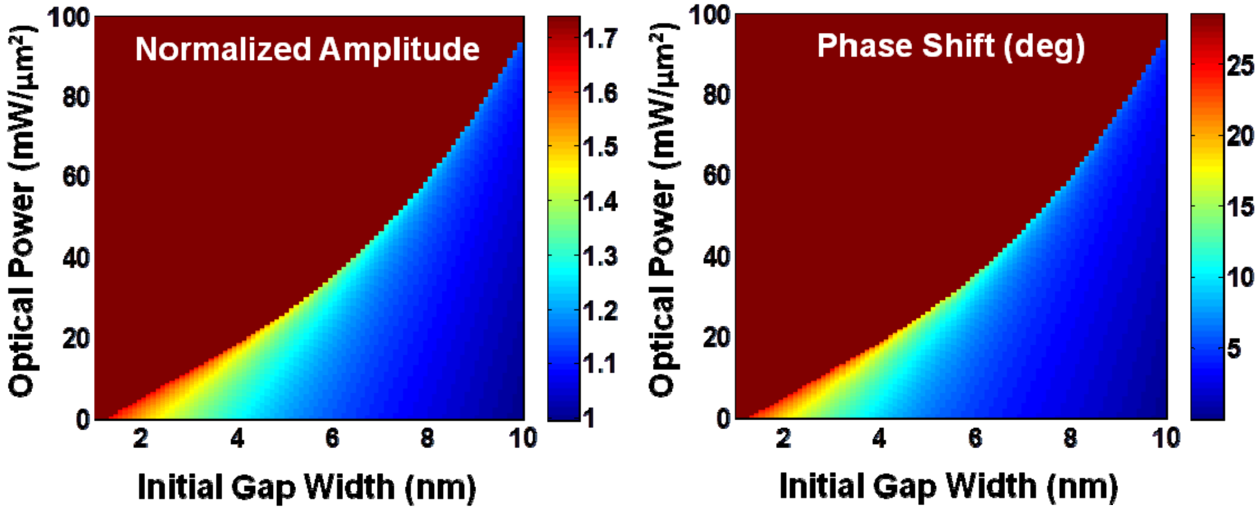

Figure 4 Amplitude (Left) and relative phase (right) of far field at the centre of the pattern. There is an abrupt change in far field pattern as a result of mechanical reconfiguration.

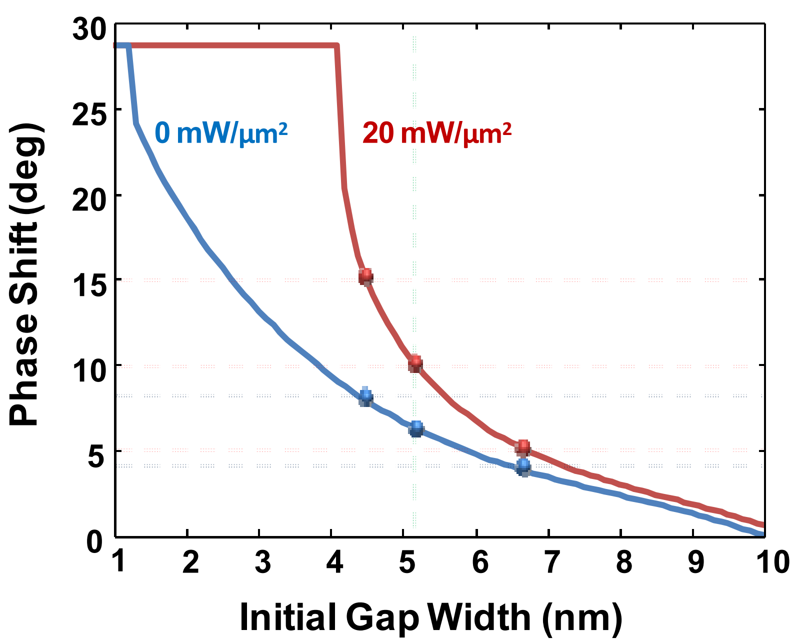

Figure 5 Relative far field phases for different initial gap width. We chose three antennas with different gap widths results in two phase shifts at zero illumination and 20 mW/um^2 illuminations.

Now, we choose three antennas with different initial gap width (figure 5). For zero gate illumination, the phase shift between them is 2 deg whereas for 20 mW/um^2 is 5 deg. Thus α can be changed by optical source power due to mechanical reconfiguration. As a result for 2.04 um wavelength, the far field beam can be steered by 0.5 deg. More elaborated optimechanical nanoantenna can be designed to get a higher angle of steering. However, this structure shows the potential application of mechanical reconfiguration in surface plasmon based optical antenna to get beam steering functionality.

4. CONCLUSION

Here we show by using mechanical reconfiguration, we can steer far field beam in an optomechanical nanoantenna phased array. Such a system has no active element to reach functionality. In such a structure, the far field can couple efficiently to near field and vice versa proposing easy way to excite the system and gather the output signal. Since surface plasmons are used to convert free space light into a subwavelength mode, such a structure can be fabricated with subwavelength dimensions which results in acceptable mechanical bandwidth.

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