Resonant elements contactless coupled to bolometric micro-stripes

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ABSTRACT

One of the main technical difficulties in the fabrication of optical antennas working as light detectors is the proper design and manufacture of auxiliary elements as load lines and signal extraction structures. These elements need to be quite small to reach the location of the antennas and should have a minimal effect on the response of the device. Unfortunately this is not an easy task and signal extraction lines resonate along with the antenna producing a complex signal that usually masks the one given by the antenna. In order to decouple the resonance from the transduction we present in this contribution a parametric analysis of the response of a bolometric stripe that is surrounded by resonant dipoles with different geometries and orientations. We have checked that these elements should provide a signal proportional to the polarization state of the incoming light.

Keywords: optical antennas, nanophotonics, resonant structures, detectors

1. INTRODUCTION

Optical antennas and resonant structures are key elements for the development of nanophotonics devices working at subwavelength scale.[1,2] When considering them as light detectors they show selective properties inherently related with its antenna character. Then, in antenna-coupled detectors, or optical antennas, we must include a transduction mechanism able to convert the electric currents generated at the antenna structure to an electric signal readable by an external circuit. Since long ago, a tunnel union has been proposed and used to construct Metal-Insulator-Metal structures located at the feed point of antennas.[3] Another mechanism, based on the dissipation of energy by Joule effect has produced optical antennas that are easier to fabricate than MOM devices. Even more, when considering the material properties of metals it is possible to print optical antennas using only one-step e-beam lithography, metal deposition and lift-off.[4] More recently, the thermoelectric conversion has been revisited as a valid transduction mechanism for these devices.[5] Seebeck effect also allowed a thermoelectric antenna polarimeter.[6]

In most of the cases presented previously, optical antennas require the existence of signal-extraction lines that might strongly affect the performance and behavior of the device.[7] These extraction lines are connected to the resonant element and become themselves resonant structures. This "parasitic" resonance may alter the expected behavior and has to to be considered from the very beginning of the design and simulation of the structures. On the other hand, when dealing with optical antennas, the signal currents and voltages travel through nanometric structures that are very sensitive to voltage peaks coming from electrostatic discharges or

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biasing circuits.[8,9] This fact makes optical antennas a quite fragile element that need special electric protection and delicate handling. In this contribution we propose a solution from the opposite perspective. Our idea is to place resonant structures close to extraction lines avoiding direct electric connection in a contactless geometry. This approach should produce tougher devices preserving the good selectivity properties of optical antennas.

In this contribution we present several geometries able to work as optical detectors. The results obtained from the simulation has been analyzed and compared with typical distributed bolometers acting as optical antennas.

2. CONTACTLESS RESONANT ELEMENTS

When antenna-coupled detectors appeared, a key advantage of them was the different role asigned to the resonant element, and the transducer.[10] When considering nanophotonics devices, the shrinking in size involves a low response as far the retrieved signal, and the signal to noise ratio, depends on the physical extension of transducers, as it happens in bolometers.[11] Then, the performance of transducers having dimensions well below wavelength is compromised. In those cases, antennas provide selectivity properties in polarization and frequency, allowing a detection area that still can be considered subwavelength but larger than the transducer. An added capability of small transducers is the fast time response, even when thermal effects are at play, because of the low thermal inertia associated with tiny volumes. However, in antenna coupled devices signal extraction lines resonances can mask the antenna response both in polarization selectivity, and also in detection area. The idea here is to change roles and avoid signal extraction lines as much as possible. Contactless resonant elements couple to a transducer structure without electric contact. Resonances in the antenna produce changes in load lines that act as bolometric tranducers. The electric field distribution around the antenna reaches those lines in close proximity, but without physical or electric contact. Those fields produce electric currents that dissipate as Joule heating. This heating changes temperature locally allowing bolometric detection. Moreover, if contactless resonant element are located close to a thermoelectric junction, this transduction mechanism may benefit from this approach too. Contactless resonant elements can also be used as optical near-field enhancers to boost resonances and responses on nanoparticules located around them. This response can trigger spectrosopic changes or induce thermal or electric variations in close load lines able to be interrogated electrically by an external circuit.

2.1 Optical simulation

As illustrated in Fig. 1, the devices proposed here are made of titanium deposited on a wafer of Si coated by a SiO_2 thin layer having a thickness of 1.2 μm. The resonant element is a dipole made of titanium with a length of 2.8μm, and 100 nm in width. The separation between dipole and load line is 500 nm. The load line, or extraction line has a width or 1.5μm. The thickness of load lines and dipole is 100 nm, allowing a single e-beamlithography, deposition, and lift-off step. The selection of materials and geometric parameters has been properly optimized and adapted to the specific properties of metals at optical frequencies,[1213] The Si wafer is assumed to extend till infinity and the back surface of the wafer is not taken into account for this calculation. Radiation is coming from the air and corresponds with a linearly polarized monochromatic plane-wave having its electric vector oriented at different directions. The value of the electric field associated with this excitation is 220 V/m. The change in the direction of polarization makes possible to distinguish between purely thermal effects, caused by the absorption of incoming radiation, and the effect of the resonant elements coupled contactless to the signal extraction circuit. The evaluation of the performance of this element has been made using Comsol Multiphysics as a finite element method well adapted to treat both the electromagnetic and thermal domains.

Signal extraction lines are big enough to not compromise the effect of the actual resonant elements. These resonant structures are located quite close to the signal extraction line and therefore, they are able to generate currents in it. These currents dissipate along the signal extraction lines producing a bolometric effect on it. This bolometric effect is the one read by the external circuit.[4] For our purposes, the signal obtained is derived from a simple phenomenological chain that is triggered by the incident optical field. Once the temperature profile is determined, the change in resistance can be given as,

$$\Delta R = \int_{-L}^{L} \frac{\rho \alpha \Delta T}{S} dl, \quad (1)$$

where ρ is the electric conductivity, α is the Temperature Coefficient of Resistance (TCR), S is the traversal section of the element, and ΔT represents the temperature profile along the longitudinal coordinate, l, of the load line. This change in resistance, ΔR, can be interrogated by an external circuit. If the signal is extracted using a current biasing source, the voltage is given as

$$V_{\text{signal}} = I_{\text{bias}} \Delta R. \tag{2}$$

In our analysis we have found that the absorbed irradiance produces a Joule heating that sets a temperature map. This map is strongly dependent on the polarization state of the incoming radiation. Figure 1 shows two temperature maps, one for each polarization. We may check that when the incident linear polarization is aligned perpendicularly to the dipole, there is a very small change. However, for a parallel linear polarization, temperature rises at the dipole location. At this point, it is important to note that the change in temperature at the load lines is mostly due to the induced currents appearing in the structure and excited by the dipole. The contribution of thermal conduction is not as important as the one coming from the induced resonances. This is due to the thermal isolation of the substrate as it has been previously evaluated.[14] This mutual interaction can be also be shown when considering the thermal effect of the perpendicular polarization. In figure 2 we have represented the temperature distribution using a different scale. We may check that the maximum temperature reaches 0.023 K in the load line just in front of the resonant element. The maximum temperature reached at the load line when illuminated by parallel polarization is 0.112 K, i.e., 5 times more than for perpendicular polarization.

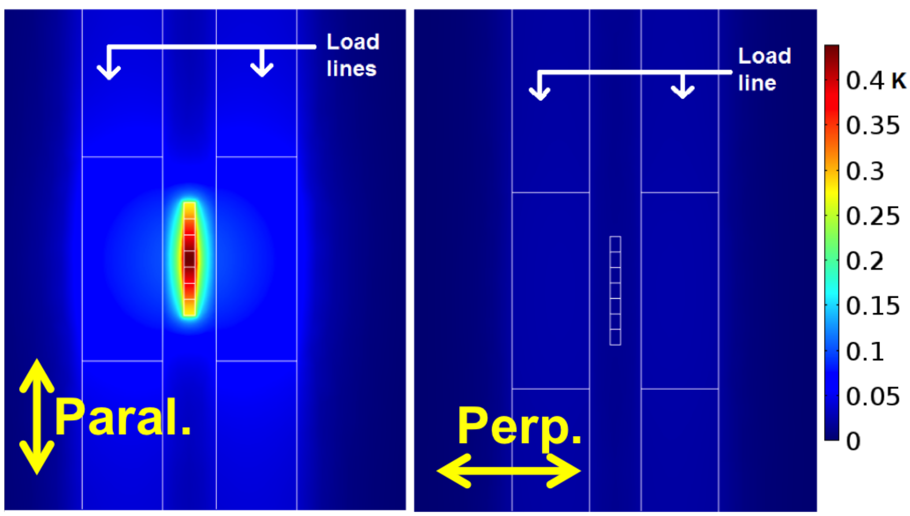

Figure 1. Map of temperature for one contactless antenna located between two load line micro-stripes. The map on the left is for parallel linear polarization, and the map on the right is for perpendicular polarization. The temperature scale is the same for both distirbutions.

To reinforce the previous findings we have plotted in figure 3 the longitudinal distribution of temperature along the load lines (left) and the dipole antenna (right). We may see that the maximum in temperature is about 4 times larger at the dipole location than at the load line. This profile distribution has been used to calculate the expected signal for this device using equation (1). Taking into account the material parameters and this temperature profile, and considering a feasible bias current of 0.125 mA, the signal given by the device is 42 μV for each load line adjacent to the dipole. This value has been obtained using equation (2). A working device should have tens, or a few hundreds of dipoles. In that case, the system should provide a signal well above the mV before any electronic amplification.

3. ANALYSIS

Once we have evaluated analytically and numerically the results obtainable from the proposed devices, we wonder how these elements can be used as optical detectors. We should recall that calculations presented in this paper

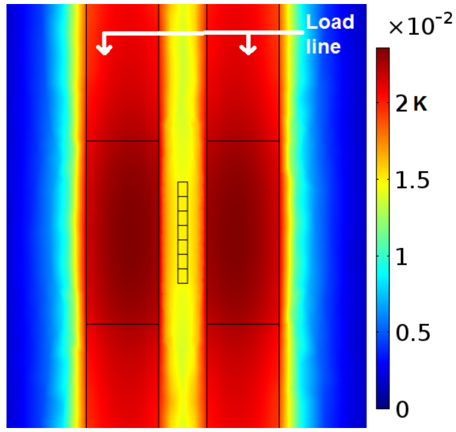

Figure 2. Map of temperature when the structure is illuminated by perpendicular polarization. This distribution is the same shown in Fig. 1 for perpendicular polarization. However, in this representation we have used a different scale map to show the thermal distribution.

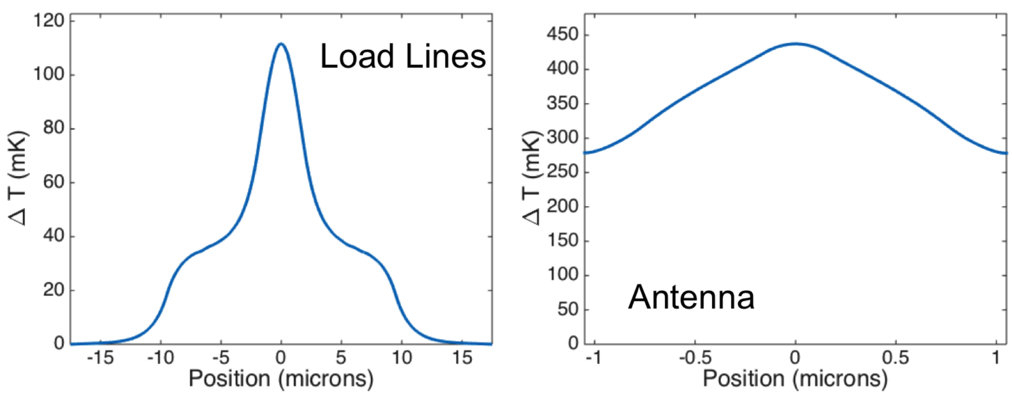

Figure 3. Profile of the temperature increment, ΔT, along the load line (left) and dipole antenna (right). The maximum temperature difference is aligned with the center of the dipole.

are given for a linearly polarized plane wave carrying an electric field of 220 V/m and impinging perpendicularly to the antenna array. A first approach to these designs can be realized using a collection of dipoles arranged in close proximity to a continuous load line. This situation is shown in Figure 4 where the dipole and load lines are placed in sandwiched geometry. This geometry can be used for parallel and perpendicular oriented dipoles, as is shown in figure 5. The zig-zag load line contains zones where resonant dipoles, in contactless configuration, are properly distributed. Figure 5.A corresponds with a parallel configuration, and 5.B has dipoles oriented perpendicularly to the load lines. This configuration should not produced a useful signal but it could be of interest to enhance the electric field between dipoles and load lines. In these previous arrangement, the distance between dipoles is also a parameter of interest because it can reinforce the effect of the resonant elements.

Another configuration that can be of interest is when resonant elements are placed above a metal patch that is separated from the resonant elements by a thin layer of a thermal and electric (DC) isolator. A simple picture of this configuration could be similar to that of figure 5.A. In this alternate design dipoles and load lines are written at different planes, and moving the dipoles to coincide vertically with the load lines. By using this approach, it could be possible to extract an electric signal from resonant elements arrays, as those configuring Frequency Selective Surface. In those structures, the ground plane can be patterned to extract an electric signal from a resonant element.

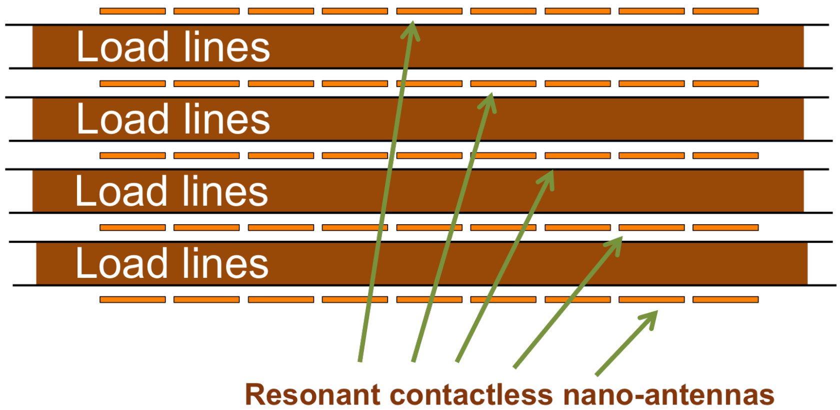

Figure 4. Practical device using contactless dipoles close to the load lines.

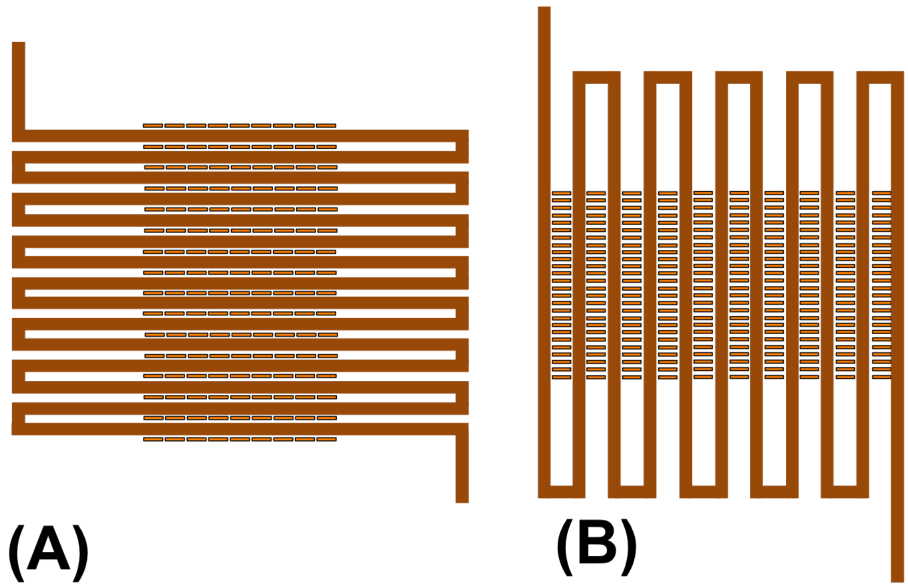

Figure 5. Spatial orientation of the resonant contactless antennas coupled to micro-stripes. Arrangement A corresponds with dipoles parallel to the load lines, and B is for an arrangement where dipoles are perpendicular to signal extraction lines.

4. CONCLUSIONS

In this contribution we have evaluated the capabilities of resonant element to induce currents in metallic structures placed at a very short distance, but maintaining a physical separation or gap. The idea is to reduce, or eliminate the effect in the overall spatial, spectral, and polarization response of load lines directly connected to the resonant antennas. Spurious or parasitic response appear when considering the whole device. These responses can mask the original signal obtained from the resonant element. By avoiding physical contact, the device seems to be less affected by auxiliary structures. However, the signal could be weaker tand some detailed analysis is necessary. Moreover, when signal voltages and currents do not travel through resonant structures, the device becomes more robust and less prone to electrostatic discharge and degradation events.

We have shown in this contribution how a resonant element placed in very close proximity to wider and more robust load lines can induce currents and dissipate power in those lines. The material and geometrical parameters of the device considered in this paper have been optimized to obtain a good response. The dissipation of electromagnetic power heats the load line that, through a bolometric transduction mechanism produces an electric signal. We have seen evaluated, using a multiphysics finite element package how the electromagnetic interaction generates a temperature distribution in the structure of interest. The maximum temperature reached at the resonant element is about 4 times larger than the maximum obtained at the load line. However, the bolometric signal for an incidence of 220 V/m is in the order of tens of μV. This signal can be larger if the interaction with resonant dipoles is repeated along a continuous load line circuit, surrounded by appropriate resonant elements. Besides, we have seen how the polarization selectivity of dipoles is still at work producing a temperature distribution (and therefore a signal) that is 5 times weaker than those obtained for a parallel polarization state.

The voltage signal can be weaker than for a connected resonant element. when considered as isolated resonant structures. However, the resonant elements can be located at different positions along the load line to cooperatively produce a larger signal. These resonant elements are modeled side by side to the load lines on the same plane and fabricated with only one lithographic process. However, this configuration is not unique and resonant elements can be place at different planes on top of a patterned load line. The induced current would produce the desired signal. With any of the configurations proposed here we could create large area bolometers with polarization sensitivity.

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