Nanophotonic optical phased arrays: opportunities and limitations

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***Abstract*—Optical phased arrays can steer a beam without mechanical rotation, thus achieving a very rapid scanning rate. The core element of an optical phased array is the pixel (unit cell) and its ability to control the phase and amplitude of the emitted/scattered light. We discuss the role of nanophotonics in achieving pixels that are small enough to avoid grating lobes, which are undesired in LIDAR applications. In particular, we designed a plasmonic pixel embedded in a conductive oxide and separated from it by a thin layer of oxide, thus forming a MOS capacitor. Applying a voltage, we can drive the MOS into accumulation and depletion, and produce a refractive index variation over a thin layer in ITO. This shifts the plasmonic resonance and modifies the phase of the reflection coefficient. We demonstrate the use of our pixel for beam steering in reflectance via 3D-FDTD simulations. We also discuss how pixel limitations, such as a limited phase range and a non-controllable amplitude of the emitted light affect the quality of the LIDAR system.**

Keywords – plasmonics, metasurfaces, beam steering, optical phased array, phase shifter, LIDAR.

DISCUSSION

Most commercial LIDARs rely on mechanical rotation to steer an optical beam. While this is an established technology, the scanning speed of a mechanical LIDAR may not be enough for applications such as self-driving cars, autonomous machines and smart communications. Research aims at realizing optical beam steering by electronically controlling the phase of each individual light emitter (*i.e.*, the pixel) in an array [1]–[4], inspired by phased arrays in the microwave regime. Waveguides and gratings can be used as pixels. However, when arranged in an array, their size leads to a large pitch (spacing between pixels). The large spacing is responsible for grating lobes, which are undesired in LIDAR applications as they can produce false positives during the scanning process. Nanophotonics research is offering new ways to realize pixels with a small size such to avoid grating lobes [5]–[8].

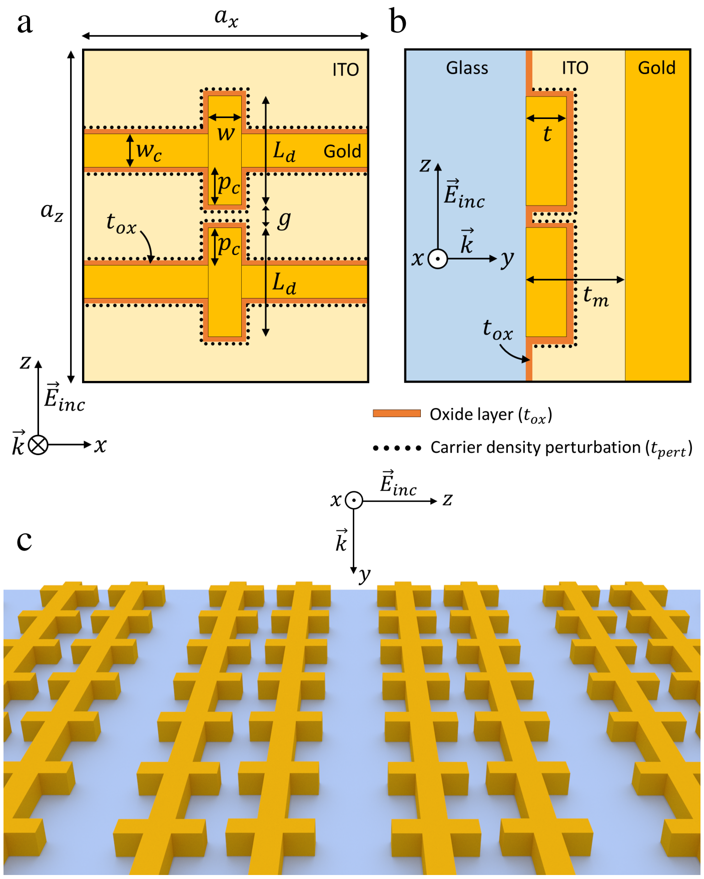

Fig. 1. Plasmonic pixel for phase and amplitude control in reflection via voltage bias: (a) Front-view and (b) side-view. (c) Sketch of the array (only nanoantennas with connectors on glass).

We introduce a plasmonic pixel to be used as the unit cell of a metasurface for beam steering in reflection [9], as sketched in Fig. 1. The pixel is composed of a metallic nanoantenna covered by a thin oxide layer, and ITO, thus forming a MOS capacitor. By applying a voltage to the nanoantenna via metallic connectors, a carrier density perturbation is induced over a thin layer ($t_{pert} \sim 1$ nm) of ITO, thus producing a permittivity variation within the thin layer. When this occurs, the environment surrounding the nanoantenna switches from dielectric to one containing a metallic shell. This abruptly changes the resonance of the nanoantenna and causes a large phase shift in its reflection coefficient. We found that the phase range of the reflection coefficient depends on the maximum carrier density perturbation induced in ITO which is bounded by the oxide breakdown field. Moreover, the magnitude of the reflection coefficient at the operating wavelength can be made uniform across the phase range by optimizing the geometrical parameters. We analyzed the performance of several pixel designs and found that a phase range of 330° is possible with a nearly flat magnitude of the reflection coefficient of 0.2; higher magnitudes of ~ 0.4 are possible if we can accept a phase range of 300°. We also found that there is an optimal position for the electrical connectors where they contribute minimally

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to the optical response of the nanoantenna. However, in an alternate position, their effect may be exploited for realizing dual-band beam steering. Though the performance of our pixel is primarily limited by the breakdown field of the oxide, the reflection coefficient phase and amplitude predicted with materials currently available are highly promising for beam steering applications, as demonstrated by 3D-FDTD simulations. We are currently investigating how to increase the amplitude of the reflection coefficient by using materials with lower losses.

To steer a beam towards a specific direction, *e.g.*, the z-axis, we must produce a phase gradient across the array along that direction. The ideal phase gradient is shown as a dashed black line in Fig. 2 – we show the modulo 2π because it is convenient for practical implementation. An ideal phase gradient for steering a plane wave requires an infinite array of infinitely small pixels with fully controllable phase and amplitude. In reality, these characteristics are not possible, and real pixels introduce imperfections in the phase gradient (see realistic phase profile in Fig. 2) – these imperfections affect the quality of the steered beam by reducing the amplitude of the main lobe and generating undesired lobes.

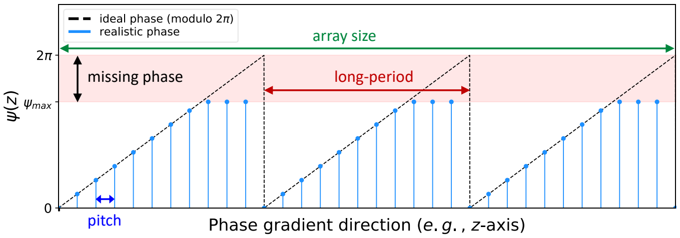

Fig. 2. Ideal *vs.* realistic phase gradient. Sources of undesired lobes are highlighted: the array size produces side lobes, the pitch produces grating lobes, and the long-period due to $\psi_{max} < 2\pi$ produces long-period grating lobes.

In Fig. 2, we highlight some of the imperfections responsible for undesired lobes. A finite array of size smaller than the incident beam produces side lobes (similarly to an aperture). As already mentioned, a pitch that is too large produces side lobes due to aliasing, so-called grating lobes. Under certain circumstances, these lobes may have similar strength as the main lobe, and they are undesirable in LIDAR applications because they may cause interfering signal returns. Furthermore, pixels for optical phased arrays could have limitations in terms of phase range and amplitude control. In Fig. 2, we show the case of a maximum phase ψ_{max} of the pixel less than 2π, which is highlighted by the red horizontal band that represents the missing phase range. Due to the phase limitation, we illustrate a compensation strategy by replacing the missing phases with ψ_{max}. This compensation strategy introduces a periodicity in the phase gradient that occurs over a "long-period" that is large compared to the pitch, and we term "long-period grating lobes" the undesired lobes associated with it. We discuss long-period grating lobes due to different phase compensation strategies and those due to a nonuniform amplitude over the phase range.

We perform our study on beam steering by using phased array theory (beams obtained through our calculations are shown in Fig. 3 for vertical and horizontal steering). Our model can take into account realistic pixel characteristics, and it allows us to propose strategies to minimize undesired lobes. By examining the strength of the side lobes with respect to the main lobe, we quantify beam steering quality, and make recommendations on the pixel performance required for beam steering within prescribed specifications. We find that many nanophotonics pixel designs allow achieving a sidelobe-to-peak ratio of 10^{-2}, which is enough for many applications. Our findings are general, *i.e.*, not linked to any specific technology, and can be used by researchers from different communities working on optical phased arrays for beam steering.

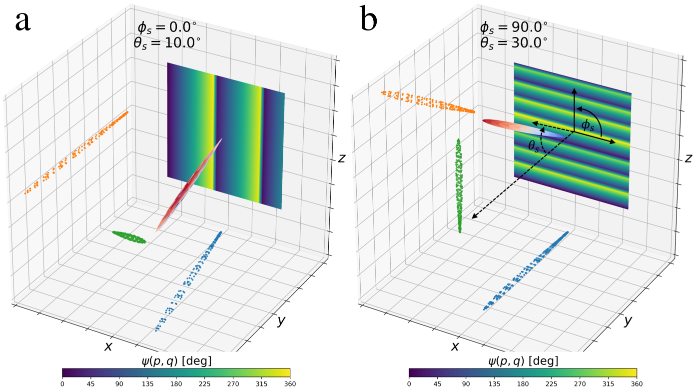

Fig. 3. (a) Vertical and (b) horizontal beam steering. The coloured square represents the phase gradient needed to realize the beam steering.

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REFERENCES

[1] P. F. McManamon, P. J. Bos, M. J. Escuti, J. Heikenfeld, S. Serati, H. Xie, and E. A. Watson, "A Review of Phased Array Steering for Narrow-Band Electrooptical Systems," *Proceedings of the IEEE*, vol. 97, no. 6, pp. 1078–1096, 2009.

[2] J. Sun, E. Timurdogan, A. Yaacobi, E. S. Hosseini, and M. R. Watts, "Large-scale nanophotonic phased array," *Nature*, vol. 493, no. 7431, pp. 195–199, 2013.

[3] M. J. Heck, "Highly integrated optical phased arrays: photonic integrated circuits for optical beam shaping and beam steering," *Nanophotonics*, vol. 6, no. 1, pp. 93–107, 2017.

[4] A. M. Shaltout, V. M. Shalaev, and M. L. Brongersma, "Spatiotemporal light control with active metasurfaces," *Science*, vol. 364, no. 6441, p. eaat3100, 2019.

[5] Y.-W. Huang, H. W. H. Lee, R. Sokhoyan, R. A. Pala, K. Thyagarajan, S. Han, D. P. Tsai, and H. A. Atwater, "Gate-Tunable Conducting Oxide Metasurfaces," *Nano Lett.*, vol. 16, no. 9, pp. 5319–5325, 2016.

[6] A. Forouzmand and H. Mosallaei, "Real-Time Controllable and Multifunctional Metasurfaces Utilizing Indium Tin Oxide Materials: A Phased Array Perspective," *IEEE Trans. Nanotechnol.*, vol. 16, no. 2, pp. 296–306, 2017.

[7] G. Kafaie Shirmanesh, R. Sokhoyan, R. A. Pala, and H. A. Atwater, "Dual-Gated Active Metasurface at 1550 nm with Wide (>300°) Phase Tunability," *Nano Lett.*, vol. 18, no. 5, pp. 2957–2963, 2018.

[8] A. Forouzmand, M. M. Salary, S. Inampudi, and H. Mosallaei, "A Tunable Multigate Indium-Tin-Oxide-Assisted All-Dielectric Metasurface," *Adv. Opt. Mater.*, vol. 6, no. 7, p. 1701275, 2018.

[9] A. Calà Lesina, D. Goodwill, E. Bernier, L. Ramunno, and P. Berini, "Optical phased arrays for LIDAR: beam steering via tunable plasmonic metasurfaces," arXiv: 1912.02275, 2019.