# Dynamic Control of Plasmonic Beams

**Dror Weisman**[1], **Ady Arie**[1]
[1]*School of Electrical Engineering, Fleischman Faculty of Engineering and the Center for Light Matter Interaction, Tel-Aviv University, Tel-Aviv 6997801, Israel*

*e-mail: drorwei1@mail.tau.ac.il*

**ABSTRACT**

We experimentally demonstrate dynamic, electrically-controlled shaping of plasmonic beams, propagating at the boundary between a metal and a dielectric, by using the thermo-optic effect. The concept is based on selectively heating a specific region in which the plasmonic beam passes by injecting electrical current to an isolated metal layer. This leads to transverse modulation of the wavefront through the thermal dispersion of the dielectric layer above this metal region. We demonstrated two active plasmonic devices: a plasmonic mode converter between the fundamental and first order Hermite-Gauss modes and a tunable plasmonic lens with a dynamically varying focal length.

**Keywords**: Plasmonic devices, Thermo-Optic effect, Active devices, Tunable lens

## 1. INTRODUCTION

Surface-plasmon-polaritons (SPPs) are electromagnetic surface waves that propagate at the boundary between a metal and a dielectric, and are coupled to collective charge oscillations in the metal [1]. Since these waves exhibit high spatial confinement together with strong intensity fields and have smaller wavelength relative to the free space electromagnetic waves, there is a growing interest to use them for many applications such as high resolution microscopy and interferometry [2,3], bio sensing, particle trapping and manipulation [4], and on-chip communication [5]. These applications depend on the ability to shape, route or switch the plasmonic beams. Dynamic control of the propagation of plasmonic waves was achieved so far using the thermo-optic effect in dielectric loaded plasmons, liquid crystals, electro-optic effect in dielectric polymers, magnetic and electro-mechanical effects [6–8], and more. Unfortunately, up till now almost all the demonstrations of these on-chip capabilities were limited to waveguide configuration [9], hence there is a lack of methods to dynamically shape the entire wavefront of plasmonic beams.

In this work [10], we used the thermo-optic effect in order to actively control and shape the wavefront of plasmonic beams. So far, this effect for plasmonic devices was mainly used in waveguide configuration, for plasmonic Mach-Zehnder interferometers (MZI) [6,11–14]. In our work, the plasmonic beam propagates along a silver-dielectric interface. We used the silver layer also as a heat resistor, hence by inducing electrical current through electrically isolated metallic region, we can change the temperature of the dielectric that is on top of it. We selected a dielectric material with a relatively large thermo-optic coefficient (TOC), Cyclomer, with $dn/dT = -(2-3)10^{-4}[1/℃]$ [13–15]. This enabled us to reach significant control over the transverse shape of the plasmonic beam in a dynamic manner with moderate levels of electrical power. By changing the temperature of the dielectric materiel in which the plasmonic beam propagates, we were able to control the changes in the dielectric's refractive index, and as a result to affect the phase accumulation difference according to the change in the plasmonic k-vector, $k_{SPP} = k_0\sqrt{\epsilon_m\epsilon_d/(\epsilon_m+\epsilon_d)} \sim k_0 n_d$, where $k_0$is the free space wave-vector, $\epsilon_m, \epsilon_d$ are the metal and the dielectric permittivity, respectively, and $n_d = \sqrt{\epsilon_d}$ is the refractive index of the dielectric [12–14] :

$$\Delta\phi = L\big(k_{SPP}(T_2) - k_{SPP}(T_1)\big) \approx L k_0 \frac{dn}{dT}(T_2 - T_1). \quad (1)$$

Where $T_1, T_2$ are two different temperatures and $L$ is the propagation length. It is clear from Eq. (1) that increasing the propagation distance and using dielectric material with higher TOC (higher $dn/dT$), increase the phase accumulation difference.

## 2. EXPERIMNETAL RESULTS

We demonstrate two active plasmonic devices based on the thermo-optic effect; a plasmonic Hermite-Gauss (HG) mode converter and a tunable plasmonic lens.

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### 2.1 Plasmonic Mode Converter

Figures 1(a-b) show illustrations of a plasmonic mode converter that enables dynamic control between a fundamental Hermite-Gauss mode with one main lobe (HG0) and HG1-like beam with two equal intensity lobes. The structure consists of two parallel stripes of silver on a BK7 substrate, where each stipe is thermally and electrically isolated from its surroundings. On each stripe we have two gratings, one to couple-in and excite a plasmonic beam and the other grating to couple it out to free space after the beam propagated in the chip and accumulated the required phase. The distance between the coupling gratings ($200\mu m$ in our design), the width of the gratings ($30\mu m$) and the gap between the stripes ($3\mu m$) determine the interference pattern. The two silver stripes are covered with a Cyclomer dielectric layer, as well as input and output grating couplers to free space light. When no voltage is applied, the temperature is the same in the two parallel stripes, and after the plasmonic beams propagate they accumulated the same phase, so constructive interference is obtained at the far field with one main lobe, similar to the fundamental Hermite-Gauss (HG0) beam. However, by applying voltage to only one of the silver stripes we also change the Cyclomer temperature and its refractive index in the layer above this stripe, thus controlling the phase accumulation difference of the plasmonic beams between the two stripes. Specifically, a $\pi$ phase difference between the two stripes causes a destructive interference at the center, thus in the far field pattern we will have two equal intensity lobes and a minimum intensity at the center, similarly to HG1 mode.

Figure 1(c) shows the experimental results of far field intensity pattern. It can be seen that without electrical current, we get a constructive interference between the plasmonic signals and therefore only one main lobe ($I = 0[mA]$). As we increase the electrical current that flows through one of the silver stripes, the interference pattern changes. For a current of $I = 37.5[mA]$ there is a destructive interference between the signals emerging from the two parallel stripes and we observe at the far field two equal-size intensity lobes. This means that we have achieved a $\pi$ phase shift between the two plasmonic signals. As we keep increasing the electrical current, we return to constructive interference ($2\pi$ phase shift) and again observe only one main lobe ($I = 50[mA]$).

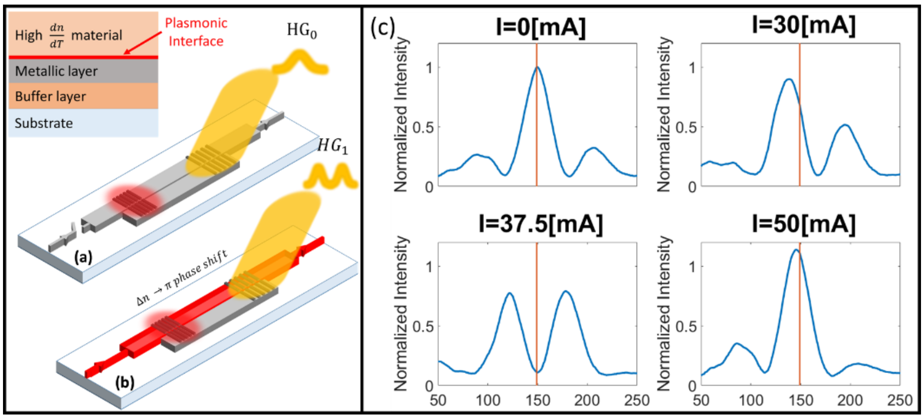


*Figure 1. (a) Dynamic mode converter from HG0 to HG1. Input and output gratings are used to excite and then out-couple plasmonic beams to free space beams. (b) Activating the phase step to half of the beam will convert it in the far field to an HG1-like beam.The image on the top left corner represents the cross section of all the structures. Measurements of dynamic mode converter from HG0 to HG1: (c) Far field interference profiles of the decoupled plasmonic beams with different induced electrical current corresponding to different phase differences between the two stripes. 0, $\pi$ and $2\pi$ phase shifts can be seen, corresponding to constructive interference with one main lobe at the center ($\Delta\phi = 0$ and $\Delta\phi = 2\pi$, for $0[mA]$ and $I = 50[mA]$, respectively) or destructive interference at the center with two equal size lobes ($\Delta\phi = \pi$, for $I = 37.5[mA]$)*

### 2.2 Tunable Plasmonic Lens

Next, we present the realization of a tunable, current-controlled plasmonic lens (illustrated in Figs. 2(a-d)). By heating a specific, thermally and electrically isolated area that will add a transverse quadratic phase to the plasmonic beam, $\phi(x) = \pi x^2/\lambda_{SPP} f$. The beam will be focused with a focal distance f. Here $x$ is the transverse axis and $\lambda_{SPP} = 2\pi/k_{SPP}$ is the plasmonic wavelength. A device with one active element of converging lens was fabricated, with similar process to the dynamic mode converter device. We measured the dynamic behavior by directly imaging the plasmonic surface and measuring the scattered signal. The device consists of a silver "island" that is isolated, both thermally and electrically. We used a symmetric concave lens shape, where each one of the two concave surfaces is a parabolic surface, in order to have a dynamic converging lens. Since the thermo-optic coefficient is negative, when the active region is activated and heated, the beam will accumulate more phase at its center relative to its sides (along the transverse axis relative to the beam propagation). In the case of no electrical current, the excited beam propagates without any perturbation. When electrical current is induced through the isolated region, only the dielectric that is on top of it will be heated and its refractive index will be changed and reduced. This will cause the plasmonic beam to accumulate a quadratic phase profile and the beam will be focused accordingly. Figures 2(e-f) show the plasmonic beam propagation image for two operation modes: without ("OFF") and with ("ON") electrical current. In the first case, the beam propagates with certain convergence, and the calculated focal length in this case, $f_{OFF} = 4.5[mm]$. When the lens is activated, and an electrical current ($I = 0.27[A]$) is induced through the isolated region, the plasmonic beam focuses and we reach to a focal length of $f_{ON} = 2.8[mm]$. This tunable plasmonic lens device has a controllable varying focal length, and the range can be tuned between the values of $f_{OFF}$ to $f_{ON}$ continuously as a function of voltage/current.

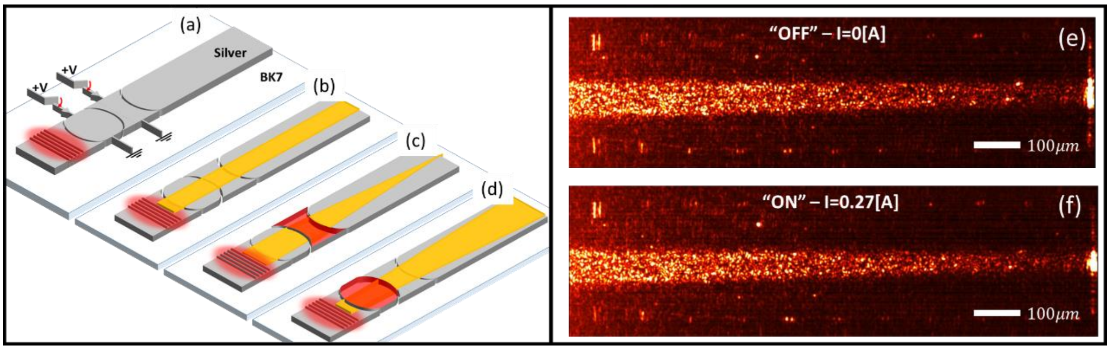


*Figure 2. (a) Illustration of a dynamic plasmonic lens, consisting of two focusing and defocusing elements. The light is coupled in through the grating coupler. (b) When no voltage is applied, the plasmonic beam (in yellow) travels unperturbed. (c) Activating the focusing element by voltage will focus the plasmonic beam, whereas activating the defocusing element (d) will make it diverge. (e) and (f) represent the plasmonic propagation pattern measurement for two cases: "OFF mode", when no electrical current is applied through the device, (e) and "ON mode", when current flows through the active region, causing the plasmonic beam to converge, thus changing the focal length of the device (f).*

In addition to the focusing device, we also fabricated a tunable diverging lens that expands the beam when being activated.

## 3. CONCLUSIONS AND SUMMARY

We experimentally demonstrated two active plasmonic devices, dynamic mode converter and tunable plasmonic lens, based on the electrically-controlled thermo-optic effect. The first device enables us to switch between two Hermite-Gauss modes, after coupling the plasmonic beam to free space whereas the second device enabled to focus the plasmonic beam when activated, on the chip itself. The method that we used in this work, of selectively heating specific isolated regions, can be further explored for other plasmonic devices, such as plasmonic beam deflector and a multi-pixel plasmonic spatial light modulator. The heating can be also done by other methods, for example by optical illumination of the isolated regions.

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