Plasmonic transmission lines: from micro to nano scale with $\lambda/4$ impedance matching

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Abstract: The downscaling of conventional RF transmission lines methodologies to subwavelength plasmonic circuits is discussed and demonstrated for a $\lambda/4$ transformer impedance matching. The nano-size transformer, matching between 0.5μm and 50nm wide plasmonic transmission lines, enhances the coupling efficiency by more than 285% compared to the direct ("end fire") coupling – i.e. harvesting more than 86% of total incident power. The influence of the transverse resonances induced by the metal claddings of the input transmission line on the light harvesting is discussed as well.

OCIS codes: (240.6680) Optics at surfaces : Surface plasmons; (050.1220) Diffraction and gratings : Apertures

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1. Introduction

Sub-wavelength Surface Plasmon Polariton (SPP) optics is of a potential use for the realization of nanometer-size photonic integrated circuits [1], for applications such as optical interconnects, signal processing and nanosensing. A major concern of theoretical interest and for practical implementation of SPP based circuits is an efficient interfacing of micron-size waveguides to tens-of-nm-size waveguides. The efficient interaction between the micro and nano scales is not evident in optics due to the crossing of a natural bottleneck – the diffraction limit. Conventional dielectric structures cannot confine light to overcome the $\lambda/2$ limit [3], while metallic structures guiding SPP can – due to the slow wave nature of the plasmons [4,5]. This property is also expressed by the extraordinary transmission of hole arrays in metallic film [6] or significant harvesting of light from regular dielectric waveguide to the nano plasmonic scale [4, 7, 8] or between two plasmonic waveguides [9].

The unique combination of metals and dielectrics in SPP guiding configurations has some resemblance to structures used in micro and radio waves frequencies (RF). Thus we expect that SPP can be guided both in nano waveguides (metal slab, stripe, wire) as well as in nano transmission line (plasmonic gap waveguide (PGW) [10], plasmonic coaxial lines [11]) where the metal boundaries are not simply connected. Here we employ the analogy between RF – transmission lines (TLs) and related SPP structures and show that TL concepts and design rules – can be applied directly to plasmonics. We demonstrate a simple design of impedance matching between a micro and a nano thin parallel plate plasmonic TL. In addition, we investigated the role of the surface waves excited at the transverse interface of the discontinuity between the plasmonic TL segments and their influence on transmission efficiency and its spectral characteristics.

2. Impedance of Plasmonic Gap Waveguide

The plasmonic TL under study is a parallel plate structure (based on PGW), with inter-metal spacing *d* and plate width *w* (considered to be much larger than *d*, - practically infinity when calculating the modal field). For perfectly conducting metal the basic guided wave is the TEM mode while in the plasmonic case the basic mode is the TM_0, which unlike the TEM wave carries a substantial longitudinal electric field (especially for very thin structures). The dispersion curve of the TM_0 plasmon mode [Fig. 1(a)] is obtained by solving the Maxwell's wave equation for a silica slab waveguide between two complex negative-real dielectrics (Au) at λ=1.55μm to yield:

$$\operatorname{tgh}\left(d\sqrt{\beta^2 - k_0^2\varepsilon}\right) = -\frac{\sqrt{\beta^2 - k_0^2\varepsilon_m}\,/\,\varepsilon_m}{\sqrt{\beta^2 - k_0^2\varepsilon}\,/\,\varepsilon} \tag{1}$$

where k_0 is the free space wavenumber, ε_m and ε are dielectric constants of the dispersive metallic cladding and dielectric core and β is the propagation constant of the plasmon mode. This dispersion curve exhibits slow wave characteristics ($n_{eff}=\beta/k_0$ larger than the actual material index) and the corresponding major magnetic field component profile which is hyperbolic also in the waveguide core [insets of Fig. 1(a)]. The shrinkage of the dielectric slab thickness enhances the slow wave characteristics and the propagation losses [4].

The characteristic impedance (Z_0) of the plasmonic (TM wave) TL is related to the TM wave impedance Z_{TM}, the latter is determined as the ratio between the transverse parts of the electric and magnetic fields [12] [Eq. 2(a)]:

$$Z_{TM} = \frac{E_x}{H_y} = \frac{\beta}{\omega\varepsilon} \tag{2a}$$

$$Z_0 = \frac{d}{w} Z_{TM} = \frac{d}{w}\frac{\beta}{\omega\varepsilon} \tag{2b}$$

where ω the angular frequency of continuous light. ε - by the definition of a waveguide configuration - is a function of the transverse coordinate(s), and thus a unique Z_0 for a mode that spread out of the core cannot be easily specified. However for highly confined optical

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fields – which are the case in plasmonic TLs, Eq. (2b) with ε value of the gap dielectric is a very good approximation.

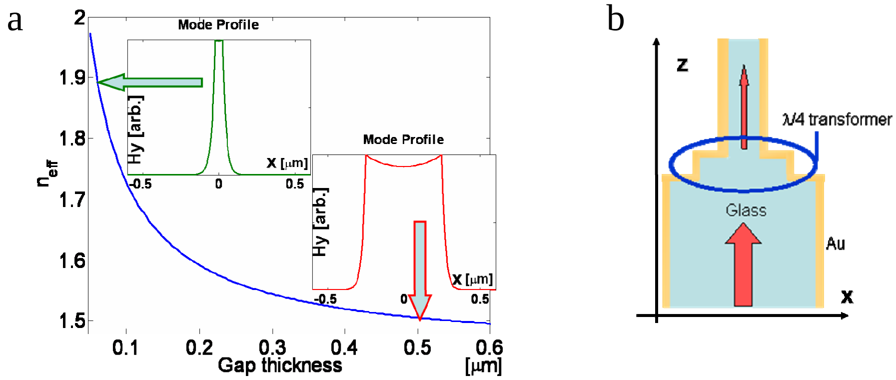

Fig. 1. (a). Gap Plasmon dispersion curve (Au cladding, Silica core, 1.55µm wavelength) – blue; major field (H_y); insets: Hy amplitude profiles at designated gap widths - red and green; (b) λ/4 impedance matching configuration.

3. λ/4 impedance matching

Using methodologies of TLs, we design an efficient transmission segment of SPPs from microscopic to nanoscopic plasmonic TL, implemented as the simplest λ/4 impedance matching transformer [Fig. 1(b)]. As a zero approximation - the λ/4 segment has characteristic impedance obtained by the geometric average of the input and output TLs impedances:

$$Z_{0\,trans} = d_{trans}\beta_{trans}/(w\,\omega\,\varepsilon) = \sqrt{\beta_{in}d_{in}\beta_{out}d_{out}}/(w\,\omega\,\varepsilon) \qquad (3)$$

The transformer parameters d and l=λ/4, assuming same dielectric material and w (TL width) for all segments, are determined by solving the coupled transcendental Eqs. (3) and (1) (the latter for each in, transformer and out segments). A solution always exists due to the monotonic behavior of the geometric dispersion of the mode [4] [Fig. 1(a)].

A specific example elucidates an efficient plasmon coupling between micro and nano-scales: the input TL width 0.5µm and output 50nm. The core material is glass having a refractive index of 1.44 and the free space wavelength is 1.55µm. From Eq. (3), the designed nano-transformer thickness is 168nm and its length is 240nm.

A two-dimensional full vectorial Finite Difference Time Domain (FDTD) simulation [13] (with perfectly matched layer boundaries) was performed by launching a plane wave at 1.55µm into the input 0.5µm TL. The Au complex dielectric constant was ε_m =-132-12.6j. The spatial distribution of the major field component at steady state is depicted in Fig. 2(a).

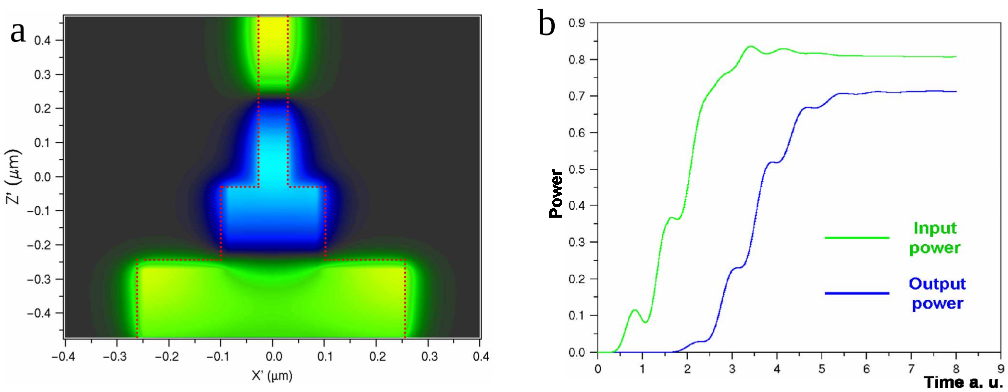

Fig. 2. λ/4 coupler (a) major field H_y (b) mode power

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The transient behavior of the power buildup in the matched plasmonic TLs is depicted in Fig. 2(b). The steady state performance of the coupler exhibits power coupling larger than 71%. For comparison, a simulation results without the impedance matching transformer (direct coupling), is shown in Fig. 3:

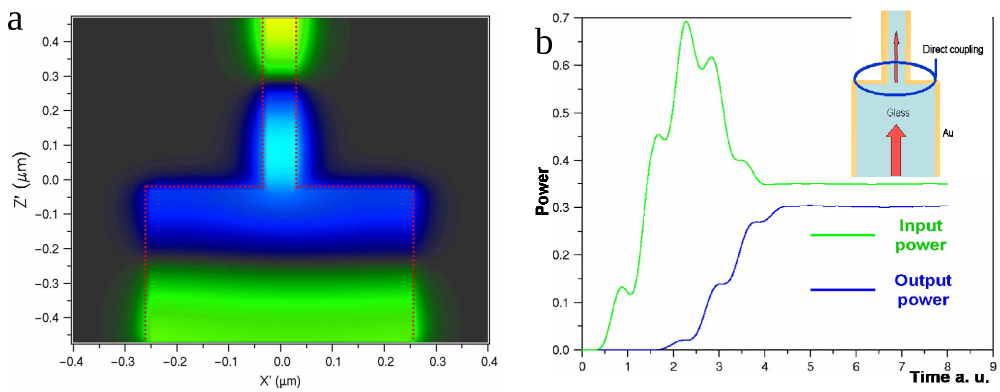

Fig. 3. Direct coupling (a) major field H_y (b) mode power

Here the power transmission is ~30%, which is less but close to the value obtained by the text book transmission formula of impedance mismatched TL segments:

$$T = \frac{4 d_{in} \beta_{in} d_{out} \beta_{out}}{\left(d_{in} \beta_{in} + d_{out} \beta_{out}\right)^2} = 0.41 \tag{4}$$

Thus the enhancement factor due to the matching transformer is 2.4, yet the transmission of the matched configuration falls short of 100%.

The reason the less-than-expected transmission of both the matched and unmatched TLs coupling, compared to the values of text-book TL formula, is the evanescent waves formed and propagating on the transverse TL junction discontinuity, which can be modeled by an additional shunt impedance (mostly capacitive) of the junction [14]. As a first order correction (the quasi static correction – valid for TL thickness below $\lambda/2$), shunt capacitance for the step discontinuity is derived from the mode matching technique [14] and the original design of quarter-wave transformer reduces to optimization problem of bivariate function minimization – length and width of the segment. The simulation results are depicted in Fig. 4, resulting in optimal dimensions of the single nano transformer segment to be 200nm both in length and width. The power transmission of the optimized segment is more than 86% (Fig. 5).

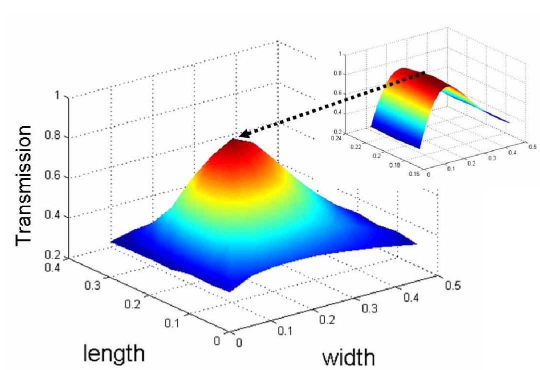

Fig. 4. Transformer dimensions optimization for maximal transmission.

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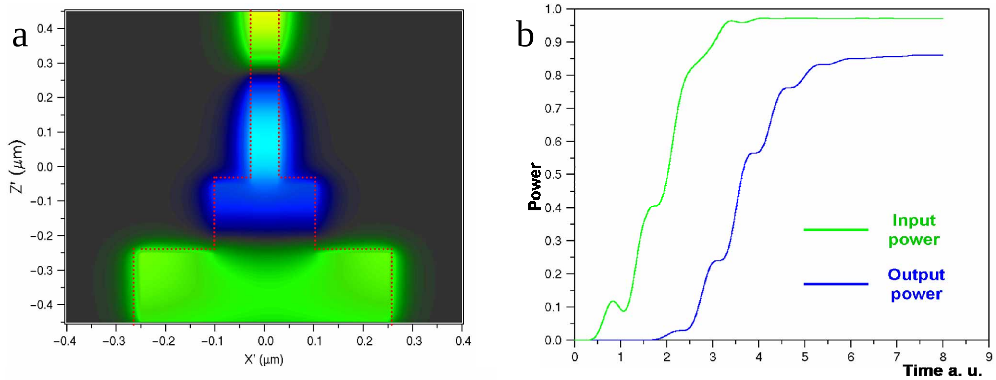

Fig. 5. Coupling with optimal transformer (a) the major field H_y (b) mode power

The coupling efficiency may be further improved by inserting additional segments. This technique used in conventional RF TL and based on Chebychev filtering design [15, 16] and may be applied directly to SPP TL.

4. Transverse resonances and harvesting

The starting point of this section is the observation that even the direct unmatched coupling yields transmission significantly larger than the mode power overlap factor (10% for our example). This higher than expected efficiency was mentioned before [8, 12, 17] and its interpretation and related consequences are discussed here.

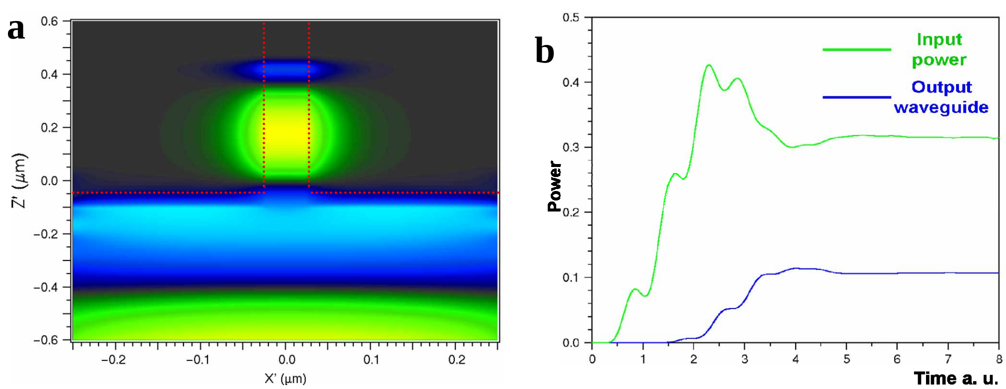

Fig. 6. Coupling of limited (d=0.5μm as in previous figures) free space plan wave (a) the major field H_y (b) mode power

When coupling (end fire) between two single mode dielectric waveguides with different core dimensions (e.g. different optical fibers) – a very good approximation to the power transmission is obtained by the overlap integral of the dominant modes. However in transmission lines (both RF and plasmonic) this calculation fails. In fact for RF TL, Eq. (4) yields transmission efficiency up to 4 times the power overlap of the TEM modes (for d_{in}>>d_{out}). The reason for this failure is the high contrast of the metallic cladding. At the junction between the TL (or waveguide) segments – the abrupt change of the transverse dimensions facilitates light coupling also into transversely propagating surface waves (either SPPs or other forms). While in a dielectric waveguide these out-propagating surface waves experience low back reflection and consequently are radiated, in TLs these waves are significantly back reflected from the metallic boundaries and eventually coupled into the output waveguide. A straightforward simulation – performed by launching the mode of the

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input TL into the output TL – but stripping off the metal boundaries of the input TL (to avoid the enhancement by back reflection), yields transmission value which is matching exactly the propagating modes overlap - Fig. 6.

These observations immediately relate our TLs coupling configuration to extraordinary transmission through slits array [17]. Here the metal walls are generating a transverse resonator which can be transformed (imaged) to an infinite replication of the output TL with a period equal to the input waveguide thickness (Fig. 7). As a consequence – we expect resonances of enhanced and reduced transmission as a function of the input TL thickness (at a fixed wavelength).

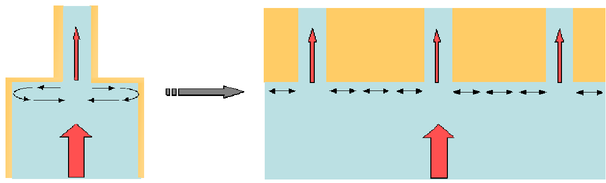

Fig. 7. TL junction and the equivalent slit array

We simulated and extracted the power transmission by varying the input TL thickness and compared it to slits arrays with respective periodicity (Fig. 8). The results show a very good match and similar spectral features – e.g. a resonance for a period which is equal to the wavelength of an SPP guided on the glass/gold interface. Figure 8 evidently shows that for the RF case [perfectly conducting cladding (PEC)] the comparison of TLs with respective slit arrays is perfect and for plasmonic TLs at the optical regime high similarity is exhibited as well. The slight shift of the resonance between the plasmonic TL and slits array cases is probably due to the fact that the reflection of the plasmonic waves from the side walls is complex which modifies the equivalent periodicity. Same reasoning may explain also the relatively high transmission of directly coupled dielectric and plasmonic waveguides reported in [8], due to the very high contrast of the input Silicon waveguides.

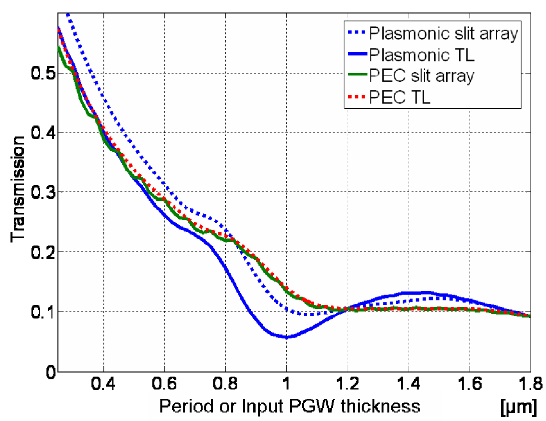

Fig.8. Extraordinary transmission of TL and slit array.

5. Conclusions

We successfully transform conventional RF techniques to plasmonic circuitry. Furthermore – it is shown that simple nanoscale segment can be used to couple very efficiently between plasmonic transmission lines with order of magnitude difference in cross-sections. 86% power efficiency was exhibited in coupling Plasmon waveguides from 500 to 50 nanometer in size. We showed the similarities between the mechanism of extraordinary transmission of slits array and the enhanced transmission of plasmonic TL in end-fire coupling scenario.

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