# Deep-Subwavelength Optical Waveguides Based on Near-Resonant Surface Plasmon Polariton

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***Abstract*** - *We discuss the feasibility of deploying two materials with close but opposite epsilon values for achieving deep-subwavelength surface plasmon polariton waveguides. In particular, waveguiding properties of a silver-silicon waveguide with a 25nm core size at 600nm wavelength are examined. Such waveguides potentially allows for ultrahigh-density optical integration.*

## Introduction

Surface plasmon polaritons (SPPs) have recently attracted a great amount of attention in achieving subwavelength optical waveguiding. Unlike in convetional dielectric waveguides, light guided by SPP waveguides does not experience a diffraction limit. Therefore mode field of such a SPP waveguide can be squeezed into an arbitrarily small size. However, it should be noticed that not all SPP waveguides reported so far have subwavelength mode field size (MFS). For example, most long-range SPP waveguides achieve relatively low propagation loss because their modal energy is largely distributed in the low-loss dielectric material. Such waveguides usually have a very large MFS. In order to deploy SPP waveguides as integrated optical circuits, one has to design true subwavelength waveguides.

To date, there are several types of SPP waveguides known for their capability in achieving subwavelength guidance, such as the gap SPP waveguide [1], and metal corner SPP waveguide [2], etc. These subwavelength SPP waveguides are however all based on geometrical tailoring. In fact, the peculiar guidance principle of SPP waveguides allows their mode field to be confined in a subwavelength fashion without resorting to geometrical tailoring. For a 1D metal-dielectric interface, the guided SPP mode has its $n_{eff}$ value defined as

$$n_{\mathrm{eff}} = \sqrt{\frac{\varepsilon_+ \varepsilon_-}{\varepsilon_+ + \varepsilon_-}}, \tag{1}$$

where $\varepsilon_+$ and $\varepsilon_-$ ($|\varepsilon_-| > \varepsilon_+$) are permitivities of the dielectric material and metal, respectively. From Eq. 1, it is noticed that $n_{\mathrm{eff}}$ can be arbitrarily large, depending on how close $(\varepsilon_+ + \varepsilon_-)$ is to zero. It follows that the transverse field decay constant in the cladding, $k_t = k_0\sqrt{n_{\mathrm{eff}}^2 - \varepsilon_{\mathrm{clad}}}$ ( $\varepsilon_{\mathrm{clad}}$ is either $\varepsilon_+$ or $\varepsilon_-$), can also be made arbitrarily large. This gives rise to the possibility of tightly confined field at the interface. A section of the interface can potentially confine light in nanodimensions in the 2D transverse domain. Such a subwavelength waveguide has the obvious advantage of being structurally very simple. A primiary reason for lack of proper study on such waveguide probably is that, in addition to the divergent propagation constant, the propagation loss will also tend to infinity as the operation is near to the $\varepsilon_+ = -\varepsilon_-$ resonance condition. In fact, the contradictory relationship between confinement and loss for SPP waveguides has been observed for a wide varieties of guiding structures (e.g. [2, 3]). In view of many published results on SPP waveguides, it has generally been accepted that some novel loss reduction technique (rather than merely geometric optimization) has to be deployed in order to make functioning integrated optical circuits based on SPP. Decreasing environment temperature [4] and using quantum-dot-based metamaterials [5] could be two viable ways to achieving the goal. Considering this factor, SPP waveguides based on a single near-resonant interface deserve as much attention as other types of SPP waveguides do in realizing subwavelength light channeling. Effectively, such a near-resonant SPP waveguide relies on material engineering, other than geometrical tailoring. In the following, from the perspective of integrated photonic circuit, we will look into a realistic waveguide design based on a finite section of near-resonant metal-dielectric interface. Our preliminary analysis is based on materials available in nature. The modal properties of the waveguide, especially its attenuation loss, will be examined. The potentials and challenges of such waveguides will be discussed.

## Realistic waveguide design

Two materials with close but opposite epsilon values (in their real part $\varepsilon'$) at certain wavelengths do exist in nature, but not without loss. One example is silver (Ag) and silicon (Si). An examination of their dispersion curves tells that their epsilon values meet our requirement around the free-space wavelength of 600nm, at which $\varepsilon_{\mathrm{Ag}} = -16.08 + 0.4434i$ [6] and $\varepsilon_{\mathrm{Si}} = 15.58 + 0.2004i$ [7]. However, these two materials are highly lossy at this particular wavelength, which is manifested by the relatively large imaginary parts of the epsilon values (denoted as ε''). A single surface mode formed by the two materials at $\lambda = 600$nm has a loss value as large as 690.7dB/$\mu$m, rendering almost any waveguide built upon such a surface impractical. One of our objectives is to investigate how small the imaginary epsilon values (ε'') of Ag and Si should be for practical applications.

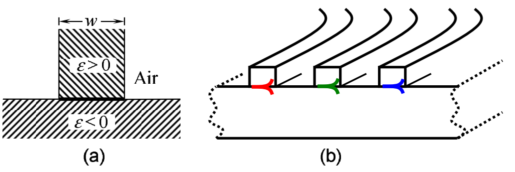


Figure 1: (a) Schematic diagram of the SPP waveguide. (b) Possible integration of the near-resonant SPP waveguides.

Figure 1(a) shows a schematic cross-section diagram of one possible waveguiding structure. The waveguiding interface has finite lateral size ($w$). The structure can be used to achieve high-density photonic integration in two dimensions on a planar substrate. Such an example is illustrated in Fig. 1(b). It should be noticed that several SPP waveguides which are similar to that sketched in Fig. 1(a) have been reported (e.g. [4]). However few of the studies have paid particular attention to achieving subwavelength guidance. First, to make sure the waveguide is single-mode, we calculate the geometric dispersion as a function of the core width $w$ at $\lambda = 600$nm (Fig. 2, left panel). Mode derivation is done in COMSOL with an electric-field- and edge-element-based finite element method. The blue curves (with dots) are the first two modes derived with ε” = 0 for both Si and Ag materials. The red dots are calculated with ε” values reduced to 1% (compared to their natural values). The mode index changes little when the ε” values change from 0 to 1%. We will show later that when losses are higher, the waveguide is too lossy to be useful. From Fig. 2, it is seen that the waveguide is single-mode when $w < 27$nm. We hence take $w = 25$nm in our following analyses. The $n_{\mathrm{eff}}$ value is $\sim$15.6 at $w = 25$nm, which ensures the mode field is highly evanescent in the cladding regions.

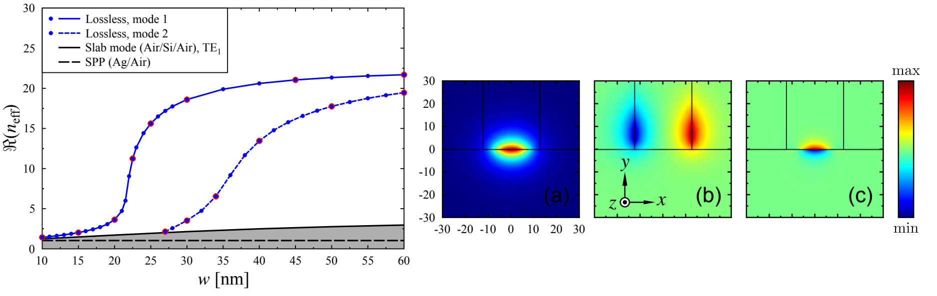


Figure 2: Left panel: Geometric dispersions of first two modes of the waveguide with respect to $w$. Loss is assumed to be zero. Red dots: the $n_{\mathrm{eff}}$ values when ε” values of both Ag and Si are reduced to their 1%. Right three panels are field plots of the waveguide with a 25nm-sized core: (a) $H_x$ field (min:0, max:1.27); (b) $H_y$ field (min:-5.02e-2, max:5.02e-2); and (c) $z$-component Poynting vector $S_z$ (min:-6.0e2, max:6.2e2). Axis unit: nm.

Mode supported by the waveguide is depicted in Fig. 2(a)-(c). The field does not change appreciably when the material losses vary from 0 to 0.1 (in fractions of their natural values). In the cladding regions, the mode field decreases to its $1/e$ over a $\sim$6nm distance. Therefore its MFS is approximated to be $37\times12\mathrm{nm}^2$. The mode field has a major polarization along $y$ direction. The $z$-component of the Poynting vector ($S_z$) shown in Fig. 2(c) confirms the highly confined energy flow in the waveguide. Notice that, although $S_z$ in Ag region is negative, the net energy flow is positive.

The loss of the waveguide with $w = 25$nm is then computed as ε” values of both Ag and Si are varied. The result is shown in a contour map in Fig. 3. ε” values of both materials are varied from $10^{-6}$ to $10^{-1}$, in fractions of their natural values. It is observed that the waveguide loss is almost equally sensitive to variations in each of the two ε” values. In practice, the requirement of propagation length depends on the application. Here, given such a tiny circuit cross-section, a loss level of 1dB/$\mu$m (corresponding to a propagation length of a few micrometers) could be suitable for a wide range of purposes. A circuit with over 100 length-to-crosssection aspect ratio permits necessary waveguide bends for forming basic components (coupler, interferometer etc) and inter-connecting various ports in a high-density fashion. From Fig. 3, it is shown that both ε” values (or equivalently, conductivities of the two materials) have to be decreased by $\sim$1000 times in order to have 1dB/$\mu$m propagation loss. It should be noted that keeping the desired negative $\varepsilon'$ and decreasing ε” will, as dictated by the Kramers-Krönig relations, require either other (meta)materials than the materials employed here, or possibly low temperature operation.

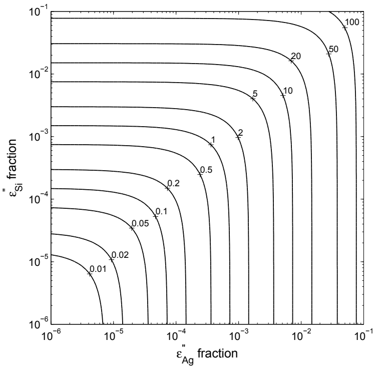


Figure 3: Contour plot of the loss values in dB/μm when the ε" values of both Ag and Si are varied in fractions of their natural values at room temperature.

## Conclusion

In conclusion, we have shown that apart from solely relying on geometrical tailoring, choosing appropriate materials can be an equally compelling approach for achieving deep subwavelength mode field size for an SPP waveguide. From practical point of view, the main concern of such near-resonant waveguides is their relatively high propagation loss. However, we foresee that once the low-loss metamaterial or loss compensation technology matures, such SPP waveguides can be potentially useful for constructing exotic miniature optical devices.

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