Design of plasmonic nano- and metawaveguides using time domain techniques

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Abstract

A number of examples of metallic plasmon waveguides for high-confinement guiding of electromagnetic energy working in different parts of the spectrum are reviewed, together with design criteria obtained via electromagnetic time domain simulations. While at visible frequencies, out-of-plane confinement below the diffraction limit is possible in simple planar geometries due to the efficient coupling of the electromagnetic field to the conduction electron plasma of the metal interfaces constituting the waveguide or in coupled-cavity geometries, at lower frequencies in the far-infrared a metamaterials approach is needed in order to engineer a plasmonic response through surface patterning.

1. Introduction

Plasmonics [1] presents a new concept for the design of highly integrated optical waveguides, allowing the breaking of the diffraction limit via the excitation of electromagnetic surface modes at the interface between a conductor and a dielectric. After a lot of breakthroughs in the design and demonstration of passive waveguide components with varying amount of confinement in recent years– ranging from mode sizes of many wavelengths down to the deep sub-wavelength regime, plasmonics is widely regarded as one of the pillars of a new infrastructure underpinning 21st photonic and optoelectronic devices [2, 3]. This paper aims to briefly highlight important considerations and constraints of plasmon waveguides operating in different parts of the spectrum, ranging from the visible to the far-infrared regime, obtained via time domain electromagnetic simulations. It is based upon various investigations carried out by the author during the last three years [4-9]. For an extended introduction and an overview of the rich history of this more than 100 year old field, the reader is referred to [1].

2. Strongly confined surface plasmon polaritons and localized plasmons

Surface plasmon polaritons (SPPs) are electromagnetic surface waves sustained by the interface of a conductor and a dielectric, set up via the coupling of the electromagnetic field with the conduction electron plasma of the metal. As a typical example, Figure 1 shows the dispersion relation of SPPs propagating along an infinite planar interface between silver and air, and for coupled plasmon modes in a silver/air/silver heterostructure.

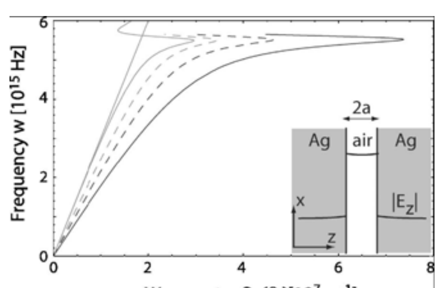

Figure 1. Dispersion relation of the fundamental coupled SPP modes of a Ag/air/Ag multilayer geometry for an air core of size 100 nm (*broken gray line*), 50 nm (*broken black line*), and 25 nm (*continuous black line*). Also shown is the dispersion of an SPP at a single Ag/air interface and the Ag/air light line (*gray line*).

For canonical simplicity, only a one-dimensional structure is considered, which allows simple analytical treatment and is sufficient for highlighting the main aspects. Here, the modes are confined in the direction perpendicular to the planar interfaces. Further examples of geometries with two-dimensional confinement and experimental realizations of plasmon waveguides can be found in [1].

As apparent from an investigation of the dispersion relation, for low frequencies SPPs constitute a grazing-incidence light field, with the modes extending over many wavelengths into the dielectric space (the dispersion curve coincides with the light line). In this regime, SPPs are also known as Sommerfeld-Zenneck waves. With increasing frequencies, the dispersion curves bend away from the respective light line in the dielectric, and the confinement perpendicular to the interface enters the sub-wavelength regime. The point where the dispersion curve bends back is given by the surface plasmon frequency, which is an appreciable fraction of the intrinsic plasma frequency of the conductor in question. At this point, the confinement is maximum (the propagation constant is largest), limited by the amount of intrinsic Ohmic damping inside the metal. As apparent, above this frequency SPPs exhibit anomalous dispersion; however this regime is highly damped, making the observation of these modes difficult. More details of the fundamentals of SPP modes can be found for example in the classical review by Raether [10].

From a waveguide design point of view, the most important aspects are that SPPs (at a single interface) allow sub-wavelength confinement only for frequencies close to the intrinsic plasma frequency of the conductor, i.e. for the noble metals only at visible frequencies. These highly confined modes enable the design of waveguides with mode areas below the diffraction limit, however only with a trade-off between confinement and loss: The more the mode is confined to the metal/dielectric interface, the higher the fraction of the mode in the metal itself, leading to large Ohmic losses. One of the most promising geometries for practical applications of guiding with sub-wavelength confinement yet wavelength-scale propagation lengths are metallic slot waveguides [11], the two-dimensional analogue to the coupled modes presented in Figure 1. Another example are coupled-cavity plasmonic waveguides, consisting of regular arrays of metal nanoparticles with deep sub-wavelength spacing [5]. Efficient near-field coupling upon excitation in the vicinity of the fundamental particle plasmon resonance results in energy transport along the array (Figure 2). A more general discussion of the trade-off between localization and loss including the critical definition of figures of merit can be found in [12].

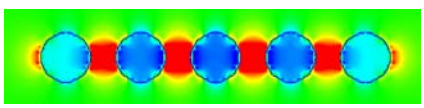

Figure 2. Time domain simulation of the electric field profile in a metal nanoparticle plasmon waveguide operating at visible frequencies.

3. A fiber-coupled surface plasmon waveguides for telecommunication frequencies

A plasmon waveguide utilizing a concept different from that of SPPs at planar interfaces is presented in Figure 3. Here, the waveguide consists of an array of metal (Au) nanoparticles arranged regularly on top of a thin silicon membrane. As apparent from the calculated mode profiles (2b, c), the mode is confined in the perpendicular direction to sub-wavelength dimensions due to a hybrid surface plasmon / Si membrane mode. In order to achieve transverse confinement, the size of the nanoparticles decreases to both sides of the central particle, and in practice only a few lateral periods are necessary to achieve wavelength-scale transverse confinement. The confinement therefore relies on a mixture of concepts from plasmonics and photonic crystals (more details can be found in [8]).

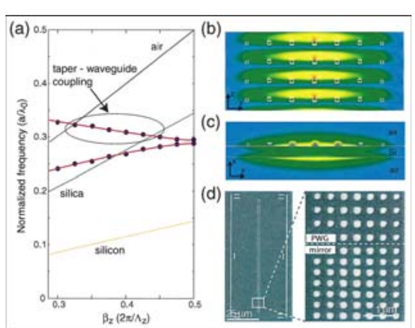

Figure 3. Three-dimensional finite-difference time-domain simulation of a plasmon photonic crystal waveguide. (a) Photonic band structure (blue dots) showing phase-matching of a waveguide mode with the silica light line. The red line connecting the dots is a guide to the eye. (b) Electric field distribution of this mode in top view (Au metal dots outlined in white). (c)Lateral distribution of the electric field for this mode through silicon membrane. (d) Scanning electron micrograph of waveguide including end-mirrors fabricated from Au nano-dots on SOI, showing the lateral grade in Au dot size.

As apparent from Figure 3a, the upper branch of the waveguide modes crosses the light line of silica, enabling phase-matching with modes of optical fibers. The mode can therefore be excited in a straight-forward fashion via contra-directional coupling to the fundamental mode of a fiber taper placed in close proximity on top of the waveguide [9].

4. Engineered plasmonic modes in the far-infrared

At far infrared frequencies, metals approach the limit of perfect conductivity, leading to negligible confinement of SPPs, which now resemble a grazing incidence light field, and at 1 THz (wavelength 300 μm) extend over many centimetres into the air space above. In order to obtain modes akin to confined SPPs at visible frequencies in this regime without a switch to a different material system with lower intrinsic plasma frequency (such as highly doped semiconductors), a metamaterials approach has to be used. In fact, it has been shown that even perfect metals can sustain SPP-like modes if their surface is structured with a regular array of holes with sub-wavelength periodicity, with an effective plasma frequency controlled by geometry alone [13]. This allows the design of SPP THz waveguides with wavelength or even sub-wavelength scale out-of-plane confinement, an example of which is presented in Figure 4. More details can be found in [7].

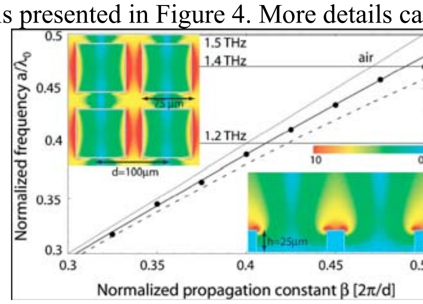

Figure 4. Dispersion relation of the surface mode sustained by a perfect conductor patterned with square holes of width a=75 μm and depth h=25 μm arranged on a square grid of lattice constant d=100 μm. Data points show calculations using FDTD simulations and the continuous line results from an analytical solution. Also shown is the analytical dispersion relation for holes with infinite depth (broken line). The insets show top and side views of the absolute value of the electric field of the mode at the zone boundary on a linear color scale.

5. Conclusion

Examples of SPP waveguides based on metals operating in different parts of the electromagnetic spectrum have been presented. While for frequencies close to the intrinsic plasma frequency of the metal sub-wavelength mode confinement can be achieved for planar interfaces, at lower frequencies a metatmaterials approach is needed in order to engineer an effective plasma frequency in this regime. For all geometries, time domain simulations provide important design criteria for the dispersive and spatial mode properties of the waveguides.

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