Sub-wavelength confinement in metamaterial filled-slot waveguide

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Abstract: We study a metamaterial-based optical waveguide formed by a silica-filled slot in a layered metal-dielectric slab. This geometry results in very strong confinement of a quasi-TE fundamental mode and gives smaller propagation losses than a purely metallic slot waveguide.
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1. Introduction

In recent years, much attention has been paid to sub-wavelength confinement of light in optical devices. The creation of waveguides that are only tens of nanometres in width will be a substantial contribution to areas such as optical switching, photonic modulation and sensing.

The sub-wavelength confinement of light can be realized, for example, by using a layered metal-dielectric slab waveguide [1], or plasmonic waveguide [2, 3] or dielectric slot waveguide, as first realized by *Almeida et al* [4]. The latter approach is of particular interest since it can result in enhancement of non-linear and electro-optical effects [5]. The incorporation of metal considerably increases absorption losses, while for the solely dielectric case the propagating mode always expands to occupy the slab regions on either side of the slot. In this work we address the problem of light confinement at the nano-scale, by combining a slot waveguide approach with the multi-layer dual slab geometry. We study the optical coupling into such a structure at 1550 nm and find a best metal-dielectric fraction which gives confinement that is 99% higher (with respect to electric field values inside the slot) than the purely dielectric case and propagation losses that are three times lower than for the purely metallic case.

2. Waveguide design

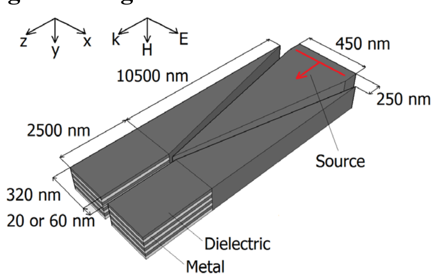

Fig.1a – Slot waveguide with coupler

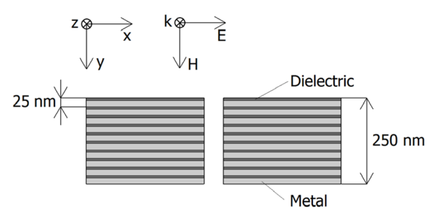

Fig.1b – Cross-section of the slot waveguide

The slot waveguide (Fig. 1a) consists of two high-index slab regions separated by a narrow low-index slot, where propagating light is confined. This happens because of the continuity of the normal component of the electric flux density *D* at the slot-cladding interface [4]. In our case the slab regions on either side of the slot consist of ten 25 nm thick *Ag/Si* pairs (Fig. 1b). The whole slot waveguide (including slot regions and surrounding media) is embedded in silica ($n_{SiO2} = 1.444$). Silver is modeled using a Drude model and silicon is considered to have a refractive index of $n_{Si} = 3.528$. Since the filled slot waveguide only provides strong confinement for modes with their main electric field component directed across the gap (the *x*-axis in Fig.1a and Fig. 1b), modes with their main electric field component along the gap (the *y*-axis in Fig.1a and Fig. 1b) leak into the slab regions and rapidly decay [1].

The direct coupling from a conventional strip waveguide to the slot waveguide at infrared frequencies may be very inefficient for waveguides with gaps narrower than 100 nm, because of the significant differences in optical mode distributions. Coupling can be improved by combining two complimentary tapers between waveguides [6]: the strip waveguide end is tapered and inserted into the silica filled slot; both sides of the slot waveguide are also tapered to form a silica-filled Y-shaped channel pattern and fit with the tapered end of the strip waveguide (Fig. 1a). As the width of the taper reduces, the radiation from the strip waveguide starts leaking into the two silica filled gaps between the complimentary taper regions. These gaps also become narrower, in total, as the wave propagates further, and they eventually merge to form a single silica filled slot.

3. Numerical analysis

The discussed slot waveguide has been designed to operate at 1550 nm and has been modeled using Finite Difference Time Domain (*FDTD*) software. The light source is placed at the beginning of the taper and light propagates in the z-direction, with its the main electric field component E_x orientated across the gap (*TE* polarized mode). The modal confinement can be evaluated by comparing the electric field strength inside the waveguide for solely dielectric, for solely metal and the intermediate *Ag/Si* combination, which is chosen to be 15/10 nm. E_x is recorded at equidistantly spaced points of the x-y cross-section, close to the slot waveguide end. The values at intermediate points are approximated by cubic Hermite spline functions. The distributions of electric field strength E_x expressed in logarithmic scale are presented in Fig. 2a-c for 60 nm slot width. The purely dielectric waveguide (Fig. 2a) does not provide strong confinement in the slot region, although there is an electric field enhancement: the mode inside the slot spreads into the silicon regions and forms a symmetric fundamental mode. The magnitude of the modal electrical field is approximately seven times smaller than the value for a slot confined mode. The confinement in the layered slot waveguide with a silver/silicon ratio of 15/10 nm is drastically improved, as is shown in Fig. 2b. While some modal power still remains in the multi-layer slab regions, the electric field strength there is only 0.01% of the value in the slot. Finally, the purely metallic slot waveguide presented in Fig. 2c supports only a purely slot-confined mode and prevents any light from penetrating significantly into the adjacent silver layers. The field profiles for a 20 nm silica filled gap demonstrate similar behaviour.

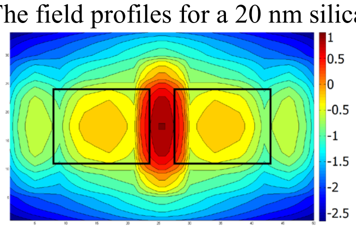

Fig. 2a – E_x profile on logarithmic scale for 0/25nm *Ag/Si* ratio

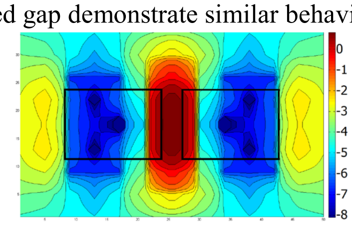

Fig. 2b – E_x profile on logarithm scale 15/10nm *Ag/Si* ratio

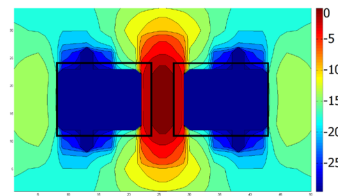

Fig. 2c – E_x profile on logarithm scale for 25/0nm *Ag/Si* ratio

The transmitted power is estimated at several discrete points along the waveguide: before the source, immediately after the source, at the end of the taper and equidistantly inside the slot waveguide. These data are then normalized with respect to the value recorded next to the source. The transmission has been studied for five different *Ag/Si* ratios, and is shown with the following notation: • 0/25 nm (only silicon), × 10/15 nm, ○ 15/10 nm, Δ 20/5 nm, □ 25/0 nm (only silver). The logarithmic plots for 20 nm (Fig. 3a) and 60 nm (Fig. 3b) slots show that the highest transmission has been achieved for a 15/10 nm *Ag/Si* ratio. The transmission for this ratio improves by 3.5 times (20 nm gap) and 2.1 times (60 nm gap) in comparison with the purely silver case. However, due to inevitable metallic losses, the transmitted power level remains much smaller than for the purely silicon case: 22.8 times less for a 20 nm slot and 6.5 times less for a 60 nm slot.

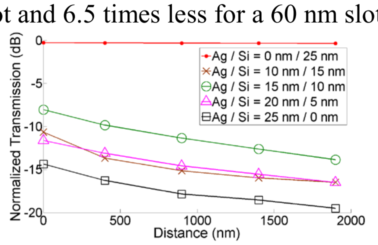

Fig. 3a – Normalized transmission for 20 nm gap

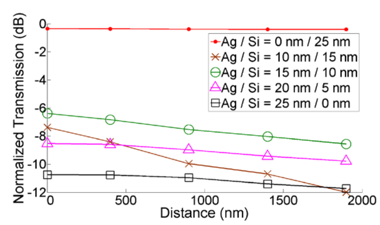

Fig. 3b – Normalized transmission for 60 nm gap

4. Conclusions

We have found that an *Ag/Si* ratio of 15/10 nm presents a best intermediate situation between solely dielectric and solely metal slot waveguides. It provides both strong sub-wavelength confinement (99% better than for an only silicon waveguide, in terms of normalization of E_x values inside the gap) and relatively small absorption losses (approximately 3 times lower than for a directly comparable silver only slot waveguide). These properties make this geometry a good candidate for construction of compact integrated on-chip micro-devices.

5. References

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