Shaping sub-wavelength plasmonic funnels

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We numerically study transmission through a silver grating with structured sub-wavelength slits. We examine a wide range of rectangular-type geometries, expanding upon previous results which considered basic triangular geometries. We identify the relevant parameters of the structure to get a narrow resonance or a broad transmission plateau in the visible or IR range. On the one hand, allowing resonances improves the maximal transmission through the grating, reminiscent of extraordinary transmission. On the other hand, when resonances are avoided very broadband, quasi-static behavior is observed in the mid-IR, which is governed by a limited number of parameters.

Introduction

Metallic gratings and apertures at the nanoscale have already been theoretically [1] and experimentally studied. Extraordinary transmission through rectangular holes or slits for example allows for very interesting transmission spectra. However, shaping of the slits gives us new features to explore. A funnel shape amongst others can improve the transmission in the visible or infrared range [2, 3]. Controlling the transmission in this way can be very useful for filters or transparent electrodes. Moreover this kind of structures can squeeze light in a very small space, which is often a desirable feature.

To understand the main phenomena in these shaped slits, we study simple rectangular geometries in order to find the relevant parameters that play a role in the transmission. We can often distinguish between resonant or quasi-static, broadband behavior. Our work is numerical in nature (finite element method, COMSOL), however some shapes should be attainable for experiments.

Infrared range

In the infrared range, we are in a quasi-static regime. There are no Fabry-Perot type resonances, so the transmission behavior is relatively easy to understand. Obviously, for straight slits, larger slits lead to higher transmission, and vice versa for the total film thickness. However, for more specific geometries (Fig. 1), there are new parameters that play a role.

For the geometries with ‘teeth’ we find that the number of teeth decreases the transmission, even when the total teeth thickness remains the same. Consequently for Fig. 1 the right structure has a lower transmission than the left one.

Figure 1: One period of gratings with ‘teeth’: one tooth on the left, two on the right. The yellow arrow represents the incident light.

Increasing the total thickness of all teeth also decreases the transmission (Figure 2). This behavior is valid for a wide range of wavelengths (3.5 - 10 nm) so we have a weak evolution in function of the wavelength.

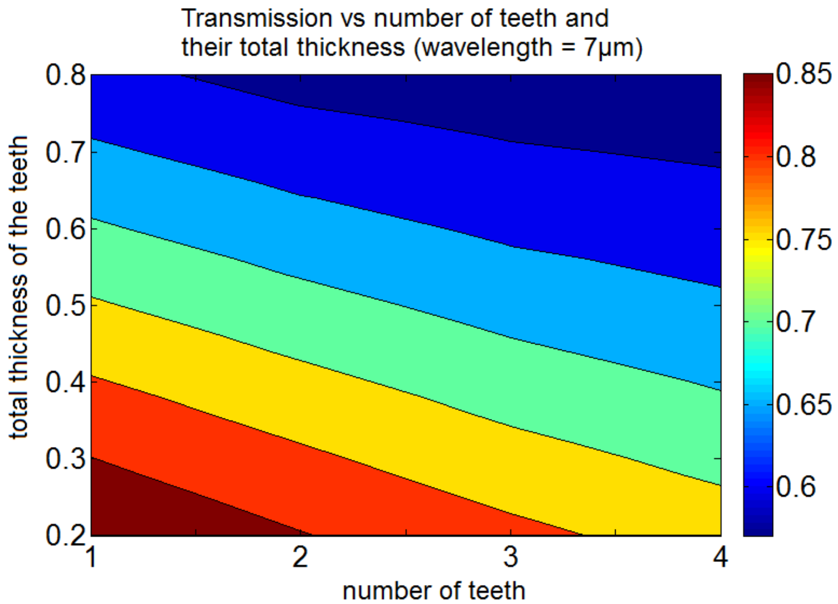

Figure 2: Transmission versus the number and total thickness of the teeth. The total thickness is the ratio of the sum of the teeth thicknesses over the total grating thickness.

Visible or near-infrared range

In the visible or near-infrared range, some resonances will occur if the structure has the necessary parameters, such as size.

Due to the different geometries, the one tooth structure has a qualitatively different behavior compared to two or more teeth. For one tooth, a resonance appears if the tooth thickness reaches a certain value. Thus, by increasing this quantity we can switch from a broadband (small) transmission to a resonance which allows higher transmission, but around a specific wavelength. This evolution if shown in Fig. 3.

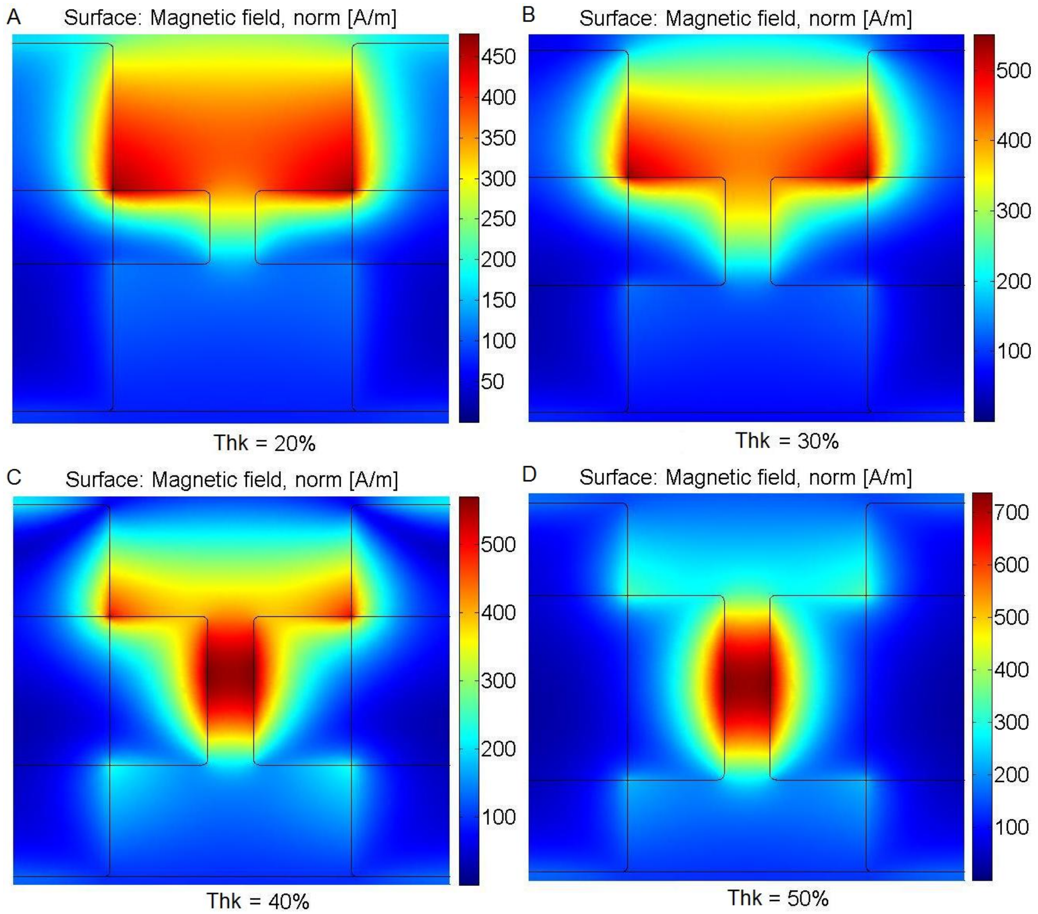

Figure 3: Magnetic field for the one tooth structure with different tooth thickness. A small thickness does not allow a resonance (A), but a bigger one can accommodate one (D). Thk is the ratio of the tooth thickness over the total thickness.

For the multiple teeth structure there is always a resonance that appear in the cavities formed by the teeth. The sum of the teeth thicknesses does not affect the resonance shape, see Fig. 4. The mode is just squeezed in a smaller space when the teeth thickness increases. The wavelength is not affected either. An origin of this phenomenon is found via the effective index. If we have more metal, the effective index of the guided slit mode increases, so the effective wavelength decreases. As a consequence, the cavity mode needs less space and can be squeezed.

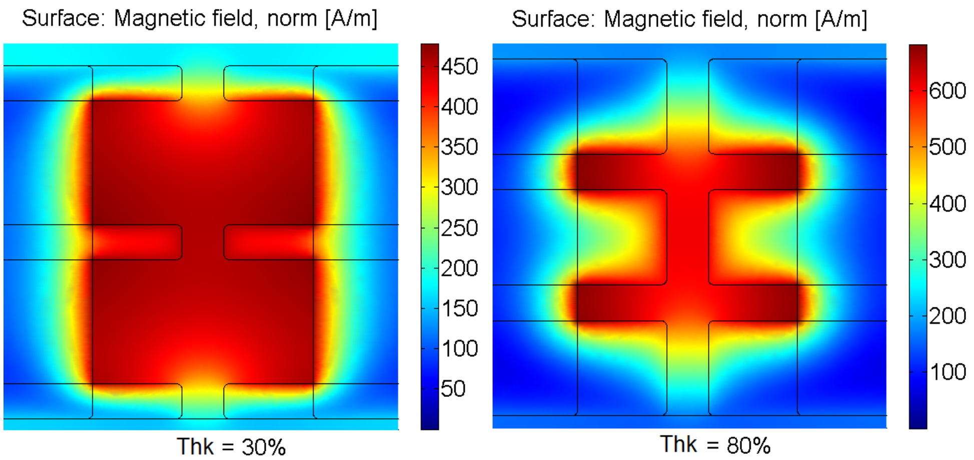

Figure 4: Magnetic field for the triple tooth structure with different total teeth thickness. This parameter does not affect the apparition of a resonance, but only squeezes the mode in a smaller space and thus increases the magnetic field.

In addition, a second order mode is allowed by the three and four teeth structures. This mode is understood via the middle teeth which make a boundary between the two maxima of the second order mode. This is not possible for a two teeth structure.

Conclusion

With rigorous simulations we have analyzed the behavior of metallic gratings with shaped slits.
In the infrared range, the properties are quasi-static and we identify the limited number of main parameters. These are mainly the parameters that characterize the aperture size(s).
In the visible range, the resonances induce a more complicated behavior. We find that some sizes need to be big enough to allow for a resonance to develop, and to create a larger, but narrow-band, transmission.

References

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