Towards perfect metallic behavior in optical resonant nanostructures: supplement

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Towards perfect metallic behavior in optical resonant nanostructures: supplemental document

This document brings additional information to research article “Towards perfect metallic behavior in optical resonant nanostructures”. It presents first how dielectric losses and index dispersion affects the response of the three-dielectric waveguide and photonic absorbing resonator. Then a brief comparison between an usual one-dielectric guided-mode resonator and the three-dielectric design is given.

1. IMPACT OF LOSSES ON THREE-DIELECTRIC STRUCTURES RESPONSES

A. Choice of dielectric indices

In the original paper, \( n_1 \) and \( n_2 \) represent two ideal dielectric materials that present simultaneously a high index contrast and losses as low as possible. As most of our results were given for a very narrow spectral window around 4 \( \mu \)m, we chose indices that match mid-infrared indices of SiO\(_2\) and Ge [1]. Besides, we did not take into account any spectral dispersion or dielectric losses to focus on the impact of the three-dielectric structuring on metallic losses. We thus simply had \( n_1 = 1.4 \) and \( n_2 = 4 \).

In this section we present again some of the results of the article considering this time index dispersion and losses in the dielectrics. We now refer to the dielectrics using their complex index \( n_i = n_i + jk_i \) with \( k_i \) the extinction coefficient of dielectric \( i \).

- A first set of results was obtained by adding a dispersion and loss rate to \( n_1 \) and \( n_2 \) consistent with the literature on SiO\(_2\) and Ge [1–3]. Figure S1 provides for the resulting indices. It seems clear that the dispersion of the index remains here negligible on such a narrow spectral band. The main impact of considering literature data is thus the introduction of losses, which are around \( 7.5 \times 10^{-5} \) for the extinction coefficient of \( n_1 \) (SiO\(_2\)) but still neglected for \( n_2 \) (Ge).

- A second set of data additionally considers the introduction of losses in the high index region. Two different situations are explored with an extinction coefficient of respectively \( k_2 = 1 \times 10^{-6} \) and \( k_2 = 1 \times 10^{-5} \). As it is shown afterwards, these two values enable to apprehend the effect of dielectric loss in the high index region.

![Fig. S1. Refractive indices \( n \) and extinction coefficients \( k \) of dielectrics 1 and 2 consistent with literature on SiO\(_2\) and Ge. Dispersion is considered for both and loss is only considered for \( n_1 \) (SiO\(_2\)) as Ge is generally assumed to be loss-free around 4 \( \mu \)m [1–3].](image-url)
B. Impact on low loss waveguide

B.1. First data set: dispersion and losses in low index region

Figure S2 reproduces Fig. 2(a) of the original article when considering dielectrics indices of Fig. S1. Before reaching $10^4$ or $10^5$, $Q$ follows the same width dependency as in the no dielectric-loss system. Above, $Q$ is still increasing with $h$ but at a lower rate. It is worth noticing that this slope break (for $\max_f(Q)$ and $Q$ at $f = 0.5$) roughly happens at $Q_{n_1} = n_1/(2k_1)$ (this would be the quality factor of a plane wave in an infinite $n_1$ substrate).

Fig. S2. Reproduction of Fig. 2(a) from original paper with dielectrics indices from Fig. S1 (dispersion and losses in $n_1$). Quality factor of the TM$_0$ mode of the three-dielectric waveguide as a function of relative width $h/\lambda$ and fill factor $f$ for a 4 µm vacuum wavelength.

B.2. Losses in both low and high index regions

Figure S3 now depicts how the introduction of losses in the high index region $n_2$ affects the evolution of $Q$ with guide width $h$. The latter seems to set a limit on the maximal value $Q$ can reach at large $h$. This limit is well described by Eq. (S1) which, similarly to the previous remark on the slope change, corresponds to the quality factor of a plane wave propagating in an infinite dielectric 2. This is incidentally quite in accordance with the concentration of the field in the high index region as the width increases. Taking the case of $k_2 = 1 \times 10^{-5}$, Eq. (S1) gives $Q_{\max} = 4/(2 \times 10^{-5}) = 2 \times 10^5$ which corresponds very well to the plateau the red and blue curves reach at large widths. As for $k_2 = 1 \times 10^{-6}$, both curves reach a value of $1.6 \times 10^6$ at $h = \lambda$, not far from the $2 \times 10^6$ value.

$$Q_{\max} = \frac{n_2^2}{2k_2}$$

(S1)

Fig. S3. Figure 2(a) left from original article with dielectrics indices from Fig. S1 (dispersion + losses in $n_1$) and an additional extinction coefficient $k_2$ in the high index dielectric. Two values are considered for $k_2$: $1 \times 10^{-5}$ of the left and $1 \times 10^{-6}$ on the right.
C. Impact on low loss photonic resonator

The introduction of losses in the dielectrics affects similarly the responses of the three-dielectric guided-mode resonator. Figure S4 depicts how the absorption peaks are modified when taking indices from Fig. S1 ((dispersion + losses in $n_1$) instead of constant and loss-free dielectrics. Three guide widths and consequently three levels of quality factors are considered. Theses additional losses thus diminishes the quality factor accordingly to the previous study on waveguides. As the relative change in dissipative damping term becomes important at large width ($h = 1.9 \mu m$), a slight modification of geometric parameters is needed to tune the radiative damping term of the resonator and thus obtain again a perfect impedance matching. This study thus shows that obtaining ultra-narrow perfect absorbers/thermal emitters is possible with realistic dielectric properties.

Even if it was presumably negligible, refractive index dispersion was also taken into account in Fig. S4 accordingly to Fig. S1. As expected, no effect can be seen.

Even if it was presumably negligible, refractive index dispersion was also taken into account in Fig. S4 accordingly to Fig. S1. As expected, no effect can be seen.

As we did for waveguides, we also investigated how the introduction of losses in the high index region affects the GMR response. Figure S5 similarly compares initial responses with responses obtained with indices from Fig. S1 (dispersion + losses in $n_1$). (a) For both curves: $h = 1.1 \mu m$, $p = 1.61 \mu m$, $L = 220$ nm. (b) For both curves: $h = 1.5 \mu m$, $p = 1.27 \mu m$, $L = 190$ nm. (c) For both curves: $h = 1.9 \mu m$, $p = 1.15 \mu m$; for blue plain curve: $L = 118$ nm and for red dotted curve $L = 200$ nm. See definition of geometrical parameters in original paper or on Fig. S7.

As we did for waveguides, we also investigated how the introduction of losses in the high index region affects the GMR response. Figure S5 similarly compares initial responses with responses obtained with indices from Fig. S1 combined to an additional extinction coefficient $k_2$. As for waveguides, this slightly deteriorates the quality factor but does not cause major modification of the response.
D. Loss increase in metallic parts: example of adhesive layers

The actual realisation of metal-dielectric interfaces often need adhesive layers as it for example the case between Au and SiO$_2$. These layers are usually composed of rather lossy metals which might slightly deteriorates the quality factor of the system. This short section describes how the introduction of a 20 nm thick chromium layer affects the quality factor of the 3-dielectric waveguide. Similar effects can be observed of GMR architecture. Figure S6 provides for a reproduction of Fig. 2(a) of the manuscript when considering such adhesives layers. The quality factor of the waveguide is indeed diminished but the overall behavior does not change. Q follows indeed the same dependency on the width of the waveguide but with a slight offset which is due to increased losses in the metallic walls.

Fig. S5. Comparison of three-dielectric GMR response at $h = 1.5 \, \mu$m with constant loss-free dielectrics and with indices from Fig. S1 combined to extinction coefficient $k_2$ in high index region. Geometrical parameters are the same as in Fig. S4(b).

Fig. S6. Reproduction of Fig. 2(a) of the manuscript with a 20 nm thick chromium inserted between gold and dielectrics. The colorbar as well as graph limits were kept the same to facilitate comparison. Chromium was modeled using a Brendel-Bormann model form [4]. As a reminder the red dashed line corresponds to the fill factors maximizing the quality factor at each width. On the right, width dependency of this maximal quality factor along dependencies at fixed fill factors is given.
2. DETAILED STUDY OF THREE-DIELECTRIC GUIDED-MODE RESONATOR

A. Comparison between one-dielectric and three-dielectric guided-mode resonator (GMR)

This section compares the response of a usual metal-dielectric GMR with the three-dielectric architecture proposed in the original paper. Figure S7 provides for the responses of both architectures optimized to exhibit a GMR resonance at 4 µm. Guide width and period are the same for both architectures. The optical index of the one-dielectric structure is set to $n_{eq}$, accordingly to Fig. 3 of the original article (a slight modification has been made to perfectly center the curve). The gold ribbon of the one-dielectric structure is tuned to achieve perfect impedance matching.

A 400-fold increase in the quality factor of the resonance is thus observed. This is not far from what was expected from waveguide analysis. Moreover the maximal field enhancement at the resonance is 20-fold higher in the three-dielectric structure ($\frac{|H_y|}{|H_0|} = 600$ against 30).

B. Full absorption spectrum of large width structures

In the manuscript, GMR responses under TM illumination are depicted over rather restricted spectral bands. The large band spectrum of a GMR of width $h = 1.9 \mu m$ - the largest width considered in the manuscript - is investigated on Fig. S8. Two types of resonances are present. We recognize harmonics of the usual guided mode resonances ((e) to (g)). These are rather spectrally far from the investigated resonance at 4 µm but remains well coupled to far field. Fabry-Perot harmonics in the widths of the guide are also observed ((b) to (d)). However these are very lightly coupled and seems not to affect much the response of the system.

Fig. S7. Comparison of the responses of a three-dielectric GMR and an one-dielectric GMR. Constant, loss-free dielectric indices are considered (values in the legend). Gold is described by an usual Drude model (see original article). For both designs, $p = 1.27 \mu m$ and $h = 1.5 \mu m$. In the three-dielectric, $L_3 = 190 \, \text{nm}$, while in the one-dielectric, $L_1 = 630 \, \text{nm}$.
Fig. S8. (a) Absorption spectrum over 2 to 6 µm of the GMR of width $h = 1.9$ µm (see Fig. 4 of original manuscript). (b) to (g) magnetic field maps under TM illumination at normal incidence at different wavelengths.

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