# Optical resonators fabricated by nanostructuring at mesa edges

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Abstract:
Optical nano-antennas exploiting localized surface plasmons have received considerable attention in recent years due to their ability to localize light and to influence light-matter interactions [1, 2]. Such resonators however require precisely controlled nanometer scale features which are typically fabricated using serial methods such as electron beam lithography and focused ion beam machining. In this work, a new class of ordered plasmonic resonators that can be made using easily accessible UV lithography and other top-down parallel processes is studied numerically and their fabrication demonstrated.

Optical dipole resonators consisting of thin metallic (Au) rods with a feed gap embedded in a dielectric (glass) are studied using frequency domain FEA (Comsol Multiphysics). These resonators are natural candidates for fabrication by the mesa nanostructuring process. Resonance is obtained when the antenna length, $2w = n \times \lambda_{eff}/2$, where $n = 1, 2\ldots$ and $\lambda_{eff}$ represents an effective wavelength, rather than the excitation wavelength ($\lambda_0$)[1].On resonance, a large field enhancement can be obtained in the gap [3]. In this study, a two dimensional geometry is adopted and a rod of thickness $t = 10$ nm (Fig 1a) is excited by a transverse magnetic (TM) plane wave with $\lambda_0 = 850$ nm. It is shown that the half wave antennas resonate even when the two feed arms are folded towards each other (Fig 1a and b) by an angle $2\theta$. In fact, the field enhancement increases slightly as the two sharp corners are brought closer.

In practice, the folded half wave antennas are realised as "dolmen" structures consisting of a horizontal segment (length = $w_h$), and two vertical segments (length = $w_v$) separated by feed gaps (Fig 1c). The exciting field is now an oblique TM plane wave with $\alpha = 45^{\circ}$. Their resonances with segment length for the symmetric case ($w_h = w_v$) is shown in Fig 1d, and for asymmetric case ($w_h \neq w_v$) in Fig 1e. In the former case it is found that for $n = 1$, only two of the metallic segments are excited (see Fig 2a), and this is because the exciting field imposes electric fields that induce a standing wave in only two but not all three segments. With asymmetric resonators, resonances can still be excited as long as $w_h + 2w_v = n \times \lambda_{eff}/2$. This is illustrated in Fig 2b where a 4th order resonance is observed. Interestingly, the maximum field enhancement is comparable in both cases. This is a key result of this study as it proves that such asymmetric antennas, which can be fabricated reliably with the proposed method, can sustain strong resonances.

The fabrication process exploits processes such as thermal oxidation, sputter deposition, and reactive ion etching (RIE) to pattern the critical dimensions, while optical lithography is used for larger features such as the spacing. The starting point is a mesa (~2 µm wide and ~3 µm tall) etched by deep RIE on a silicon substrate which is then oxidized. A conformal Au layer is then sputter deposited to a thickness of 10 nm, and finally, nanometer sized gaps are etched at the top and bottom corner of the mesa by an optimised RIE process as described in [4] by exploiting the angle dependent etch rate. The process is summarised in Fig 3a and the gap widths as a function of etch time are shown in Fig 3b. Scanning electron micrographs (SEM) of the etched nanogaps antennas shown in Fig 3d, e, & f, corresponding to different etch times.

Gaps as small as 70 nm have now been fabricated and are expected to reduce rapidly as mesas with sharper corners are considered. A key feature of this work is that a critical dimension of the antenna, $w_v$, is set by the etch depth, whilst $w_h$ is defined lithographically. Using techniques such as sidewall processing [5], both critical dimensions could be set without lithography and further work is being carried out in this direction.

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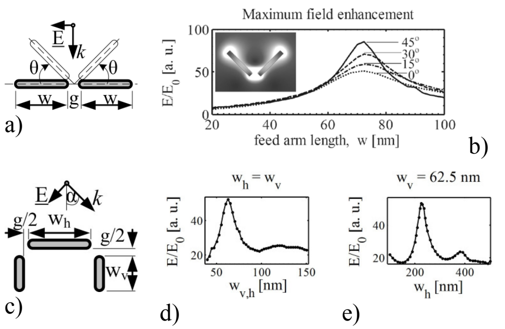

Figure 1. a) Dipole antenna with feed arms at an angle θ, b) resonance of the dipole, c) folded dipole (g = 10 nm). d) and e) show the resonance of folded dipole when d) $w_h = w_v$, and e) $w_h \neq w_v$. $\varepsilon_{metal} = -27.9-1.9j$, $\varepsilon_{glass} = 1.51^2$

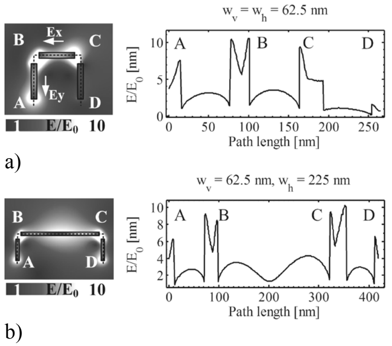

Figure 2. 2d E field map and cross section along the middle of the metal through a path ABCD (---) for (a) $w_h = w_v$ and for (b) $w_h \neq w_v$

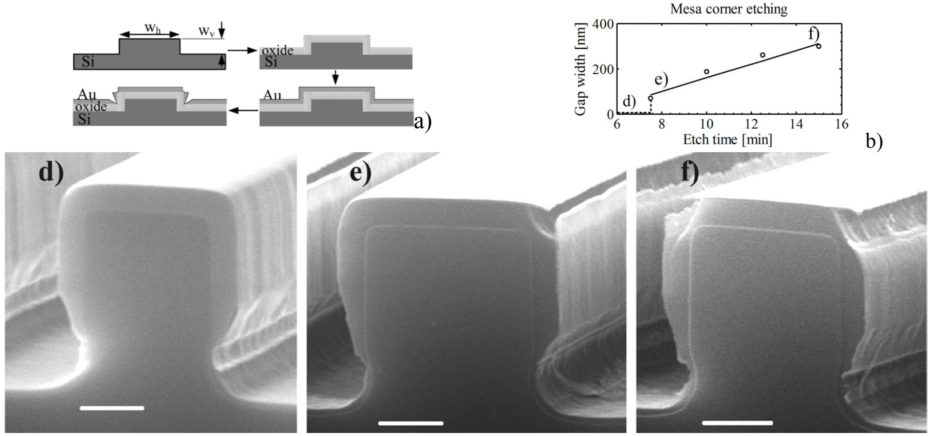

Figure 3. a) The fabrication process and b) the achieved gap widths. d), e) and f) are SEM of the cross section of the structures with no gap (under etched), g = 70 nm, and g = 300 nm. After the process in a), the $SiO_2$ was etched (12.5% HF solution) to make the gaps visible. The scale bars correspond to 1 µm.