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# Metal-insulator-metal plasmonic grating filter with suppressed Rayleigh anomaly

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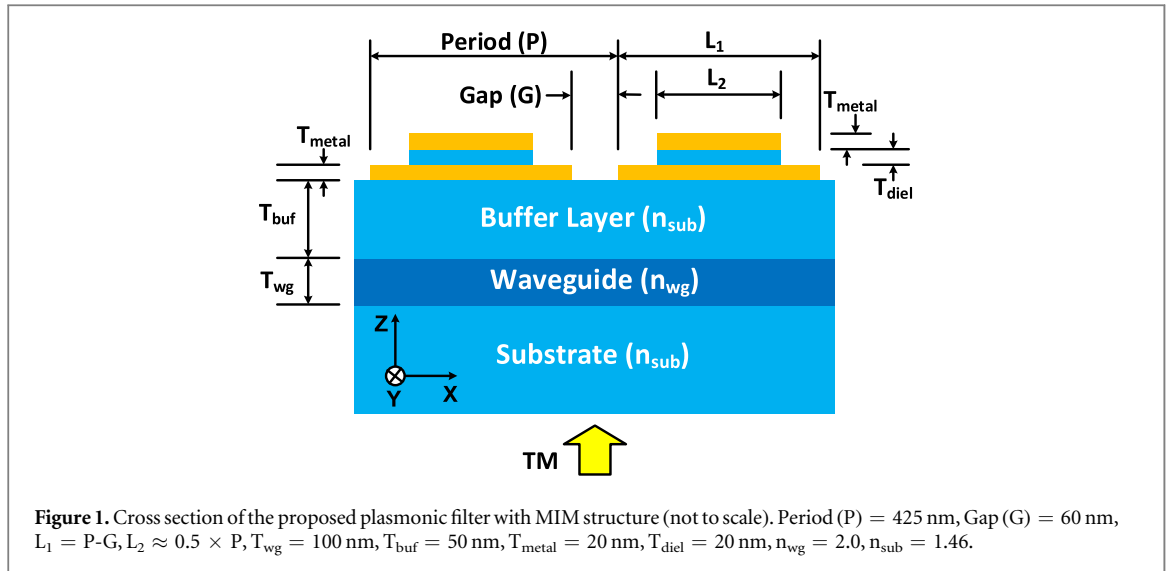
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## Abstract

Plasmonic grating filters can be fabricated in single lithography process and reduce the cost of colour filters used in hyperspectral cameras. Due to the presence of Rayleigh Anomaly (RA) peak, however, it has not been possible to design filter array spanning wide-spectral-range without sacrificing spectral purity. In this paper, a plasmonic grating filter design using Metal-Insulator-Metal (MIM) with suppressed RA peak is presented. Proposed filter allows extending spectral range without sacrificing spectral purity. Using proposed MIM structure, surface plasmon polariton (SPP) mode supported on air side of bottom grating structure is cancelled by second set of SPP mode on top grating structure. This allows designing filter array with improved spectral range and achieves better than $2\times$ improvement in suppression of the Rayleigh Anomaly peak.

## 1. Background

The color perception of human vision is limited to three primary colors: red, green, and blue. However, nature provides abundance of spectral information in the form of spectral signature, which can be used to detect and identify various materials beyond that can be done with three colors. Hyperspectral cameras are often used to capture spectrum when higher spectral resolution is needed. Hyperspectral cameras have evolved significantly in past few decades from ones with diffraction grating to snap-shot cameras with pixel level color filtering [1]. The state-of-the-art hyperspectral cameras use Fabry–Perot (FP) filters in Bayer pattern [2] to acquire spectral as well as spatial information [3]. Such approach however requires many process steps for fabricating filter array with large number of filters. In contrast, plasmonic filters allow fabricating all the filters in an array in a single lithographic process step. The first category of plasmonic filters use hole arrays (2D gratings) to achieve color filtering [4–9]. The second category of plasmonic filters are based on subwavelength gratings [10–19]. Since hole arrays usually have wider bandwidth (BW) compared to grating based filters, for applications requiring higher spectral resolution, grating based filters are preferred. Much of the review of plasmonic filters using various structural configurations can be found in [20, 21].

For most practical applications, it is required to acquire spectrum within a large spectral range. Often the entire visible range and portion of near-infrared (NIR) region is necessary for most of the hyperspectral imaging applications. This requires designing filter array spanning 400 nm to 1000 nm. However, when designing a filter array with such wide spectral range, Rayleigh Anomaly (RA) peak starts to show up in the spectrum and hence limits the performance of the filter array in terms of spectral purity. The RA was first described by Prof. Wood in his classic paper [22]. What Wood noticed and wrote in his paper was a sharp cutoff at certain wavelength in diffraction pattern, which is not explained using standard diffraction theory. Rayleigh attempted to explain these sharp transitions in diffraction pattern in another classic paper [23]. Since then, these anomalous transmission discontinuities, called RA peaks, have been the subject of many papers, in which the phenomenon is explained using various theories [24–27]. One of the methods to eliminate RA peaks is to choose ratio of gap to period in order to satisfy certain condition as described in [28]. However using this technique first order RA cannot be eliminated. In this paper, a method for suppressing first order RA peak in transmission spectrum is presented.

**Figure 1.** Cross section of the proposed plasmonic filter with MIM structure (not to scale). Period (P) = 425 nm, Gap (G) = 60 nm, $L_1$ = P-G, $L_2 \approx 0.5 \times P$, $T_{wg}$ = 100 nm, $T_{buf}$ = 50 nm, $T_{metal}$ = 20 nm, $T_{diel}$ = 20 nm, $n_{wg}$ = 2.0, $n_{sub}$ = 1.46.

## 2. Proposed filter structure

In this paper, a Metal-Insulator-Metal (MIM) plasmonic grating structure is proposed to suppress the RA in order to improve spectral purity of individual filters and hence extend the spectral range of filter array. Figure 1 illustrates the physical structure of one of such plasmonic filter with 425 nm periodicity.

Compared to prior published plasmonic filter design [29], additional metal layers (M2) separated by a dielectric layer have been added on top of the metallic grating (M1) to form MIM structure. The suppression of RA is attributed to resonant SPP mode in the metallic grating (M1) being mostly cancelled by that in M2. In regular thin metallic gratings, there are two SPP modes on either side of the metal structure which are coupled. It has been shown that they can oscillate in symmetric or anti-symmetric modes [30, 31]. In the filter being considered here, which is a thin metallic grating, the symmetric versus anti-symmetric oscillation is what makes the device with waveguide have enhanced transmission versus one without. Without the waveguide layer, the two modes oscillate in anti-symmetric manner, which means the scattered field due to abrupt termination of the top and bottom SPP modes are out of phase. In presence of a waveguide layer, the bottom SPP mode is enhanced due to resonant coupling with the waveguide mode. When the bottom SPP mode (at metal-dielectric interface) is enhanced, it strongly couples to the top SPP mode and makes the top SPP mode also resonate in phase with the bottom SPP mode. This makes the scattering field at the gaps in phase and hence there is sudden enhancement of transmission. Now at the RA point, similar phenomenon is at play. At longer than the RA wavelength, the two mode oscillate in anti-symmetric manner such that scattered field partially cancel each other locally and hence in far field as well. At shorter than RA wavelength, the two modes oscillate in symmetric configuration and hence the scattered fields add at the terminations. This is what is seen as sharp transition in transmission at the RA point, which is usually at wavelength equal to periodicity of the grating. This increase in transmission at shorter wavelength degrades the filter spectral purity.

### 2.1. Design and analysis
In the proposed scheme, an additional metal structure (M2) on top of the existing grating (M1) is proposed. Figure 2 below shows the charge configuration and resulting electric fields (not to scale) for the purpose of illustration.

By introducing another metal layer with a dielectric layer in between, there is another set of coupled SPP mode due to the MIM structure. It has been argued in [32] that such structure preferentially oscillates in anti-symmetric mode meaning that the longitudinal E-field ($E_x$) is in opposite direction. This is reasonable since if there is symmetric mode, then there would be net displacement current along the x-direction in the dielectric. With anti-symmetric mode, the bound charges (and hence the polarization) on the dielectric layer oscillate back and forth in y-direction, but not in x-direction. This is preferred mode since it has lower energy charge configuration than the symmetric mode. Now since the SPP oscillation on M2 is in opposite phase, the scattered field at the terminations are also out of phase because D-fields at the terminations need to be continuous. This results in local cancellation of scattered field from the original grating structure M1.

The analysis of truncated metal structures with resonant SPP is non-trivial due to the fact that resonance wavelength depends on reflection phase at the terminations. In dielectric waveguides, the reflection phase is easily determined by the indices of the two dielectrics at the interface. But for surface wave, it is not easy to
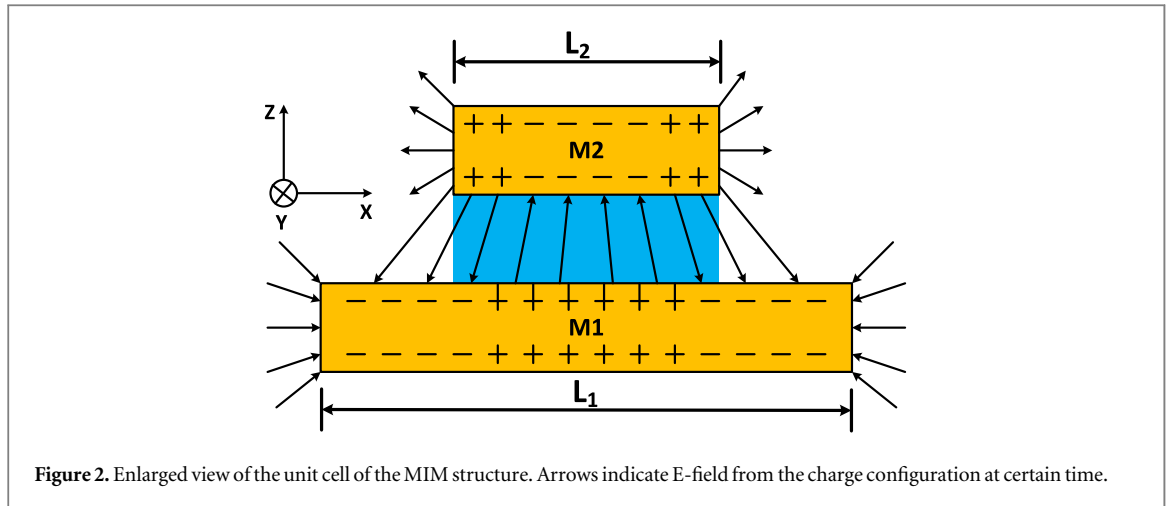
**Figure 2.** Enlarged view of the unit cell of the MIM structure. Arrows indicate E-field from the charge configuration at certain time.

calculate complex field reflectance. There have been many papers published to model the exact resonance behavior of truncated metal structures [33, 34]. Most of the analysis is for SPP waveguides in Insulator-Metal-Insulator (IMI) or MIM configuration. However, the exact nature of reflection for pure surface mode SPP with a single interface is still an open research topic. Due to the symmetry, the proposed structure is insensitive to such variation in reflection phases as long as both metal structures get terminated in the same way. In the proposed structure, although reflection phases are similar, top metal M2 is shorter than the bottom metal M1, which makes MIM formalism invalid because the bottom SPP can still propagate to the ends of M1.

Let us consider two SPP modes, one on bottom side of M2 and one on top side of M1. For these to resonate at given lengths $L_1$ and $L_2$ at the same frequency, we would need following phase matching conditions for each mode.

$$k'_x L_1 + \phi = m\pi$$
$$k'_x L_1 + \phi + k_x(L_1 - L_2) = n\pi \tag{1}$$

Here $\phi$ is the unknown reflection phase, $k_x$ is the propagation constant with air on one side of the interface and $k'_x$ is the propagation constant with Silicon Dioxide ($SiO_2$) on one side of the interface and m and n are integers. Now after simple algebra we can find that:

$$L_1 - L_2 = (n - m)\frac{\pi}{k_x} \tag{2}$$

This is independent of reflection phase. The Rayleigh Anomaly peak occurs at $k_x = 2\pi/P$, where P is the period and hence the resulting criteria for coupled resonance is:

$$L_1 - L_2 = (n - m)\frac{P}{2} \tag{3}$$

$L_2$ needs to be less than $L_1$ since if M2 is equal to or larger than M1, it will block the scattered field from M1. Therefore, n must be larger than m and since the cancellation must be at RA wavelength, $\lambda_{RA} = P \approx L_1$ and considering lowest order mode with m =1, n must be 2. This means the difference in lengths needs to be approximately half of the period when considering the gap G to be small compared to $L_1$ and $L_2$. Since higher order RA peaks occur at shorter wavelengths, only the first order RA peak is considered and suppressed using proposed technique.
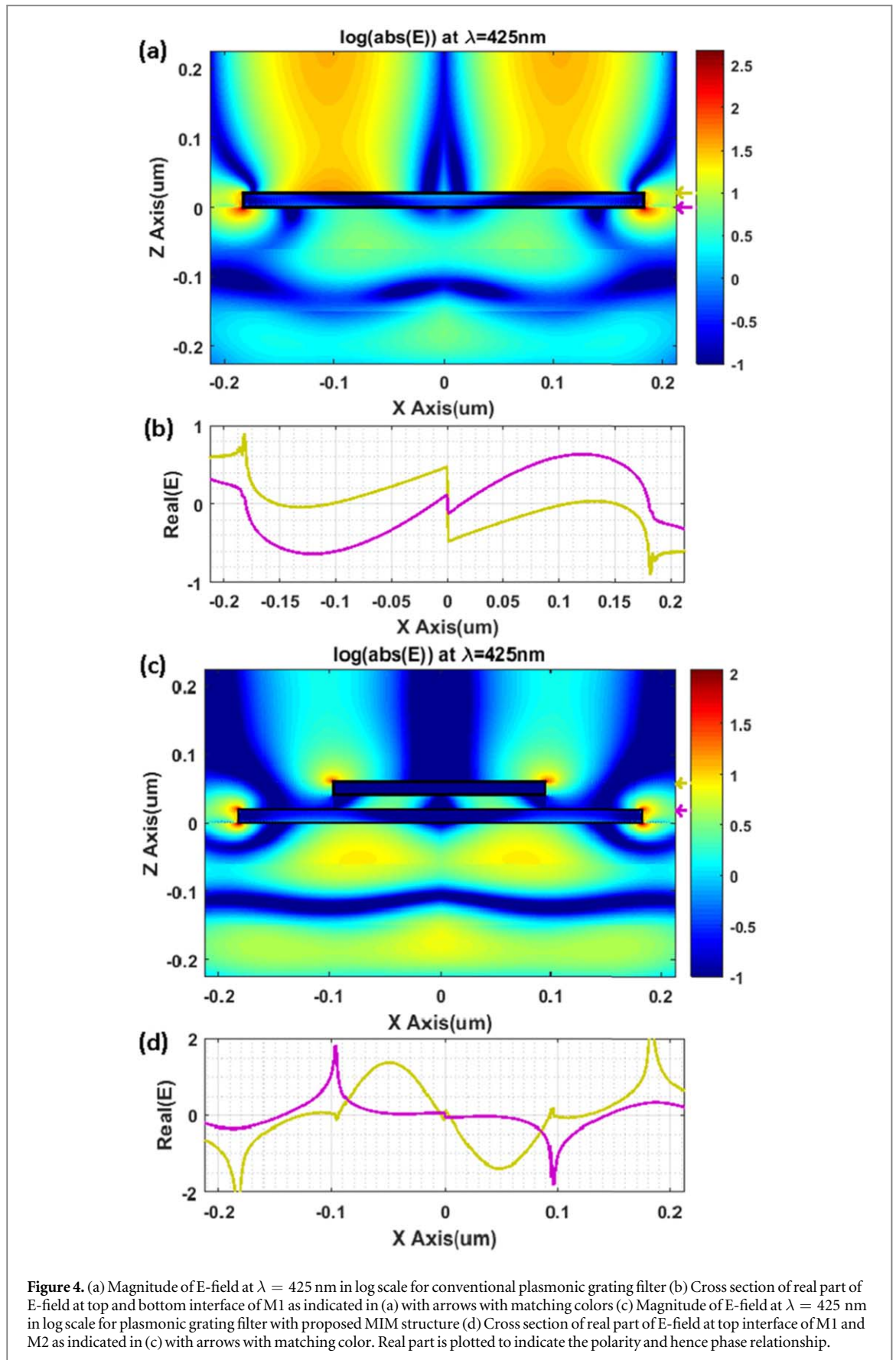
## 2.2. Simulation

As mentioned before due to coupled SPP resonances at multiple interfaces and due to the lack of proper analytical method to evaluate scattering of SPPs at terminations, numerical simulations need to be used to evaluate the performance of the proposed scheme. In this paper, Rigorous Coupled Wave Analysis (RCWA) technique was used to simulate the structure. Figure 3 shows transmission spectra with and without proposed structure at various periodicities.

The transmission without MIM structure clearly shows strong RA peak at wavelength equal to the period of the grating. Such undesired peak will introduce significant mixing of optical power from RA peak to the main peak. Such mixing cannot be completely corrected by using numerical techniques or calibration techniques and hence poses a significant problem. Using proposed MIM structure, the peak ratio could be improved by more than 2 times across wide wavelength range. To further validate the proposed design a field simulation was done at RA point ($\lambda = P$) and results are shown below in figure 4.
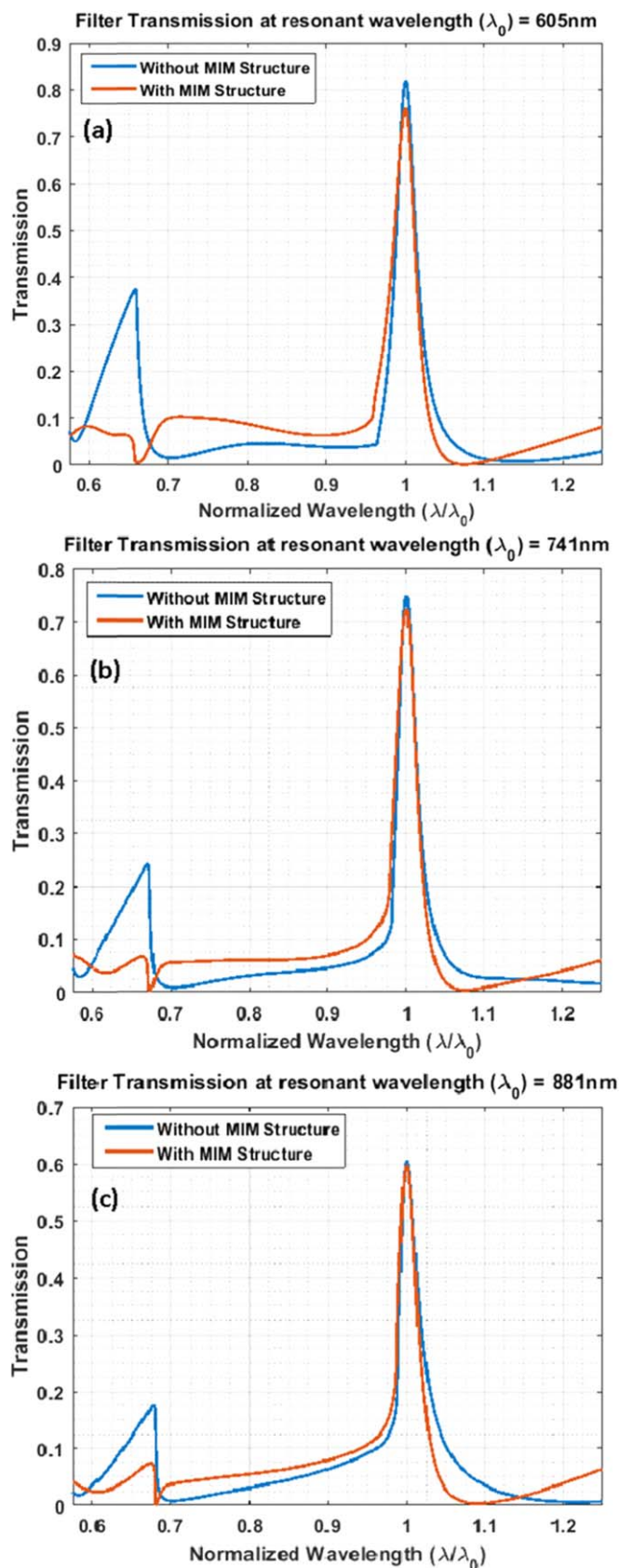
**Figure 3.** Transmission Spectra of Plasmonic Grating Filter with (red) and without (blue) proposed MIM structure at various grating period. (a) 400 nm, (b) 500 nm and (c) 600 nm. The proposed filter improves desired to undesired peak ratio (extinction ratio) from 2.2 to 7.6, 3.0 to 9.7 and 3.4 to 8.0 respectively.

**Figure 4.** (a) Magnitude of E-field at $\lambda = 425$ nm in log scale for conventional plasmonic grating filter (b) Cross section of real part of E-field at top and bottom interface of M1 as indicated in (a) with arrows with matching colors (c) Magnitude of E-field at $\lambda = 425$ nm in log scale for plasmonic grating filter with proposed MIM structure (d) Cross section of real part of E-field at top interface of M1 and M2 as indicated in (c) with arrows with matching color. Real part is plotted to indicate the polarity and hence phase relationship.

From figure 4(b) we can clearly see that two SPP modes are symmetric at RA when there is no MIM structure and hence the scattered field at the terminations are also in phase. This is the main reason for RA peak in conventional Plasmonic Grating Filters. As we can see from figure 4(d) the two SPP modes (one on M1 and other

**Figure 5.** Sensitivity to process variations. The width of MIM structure was varied from 0.2 to 0.8 × Period and the horizontal shift in location of M2 structure with respect to M1 was varied within ±0.2 × Period. It can be seen that design has large tolerance around centre point. Contour shows the design space where peak ratio is greater than 7.
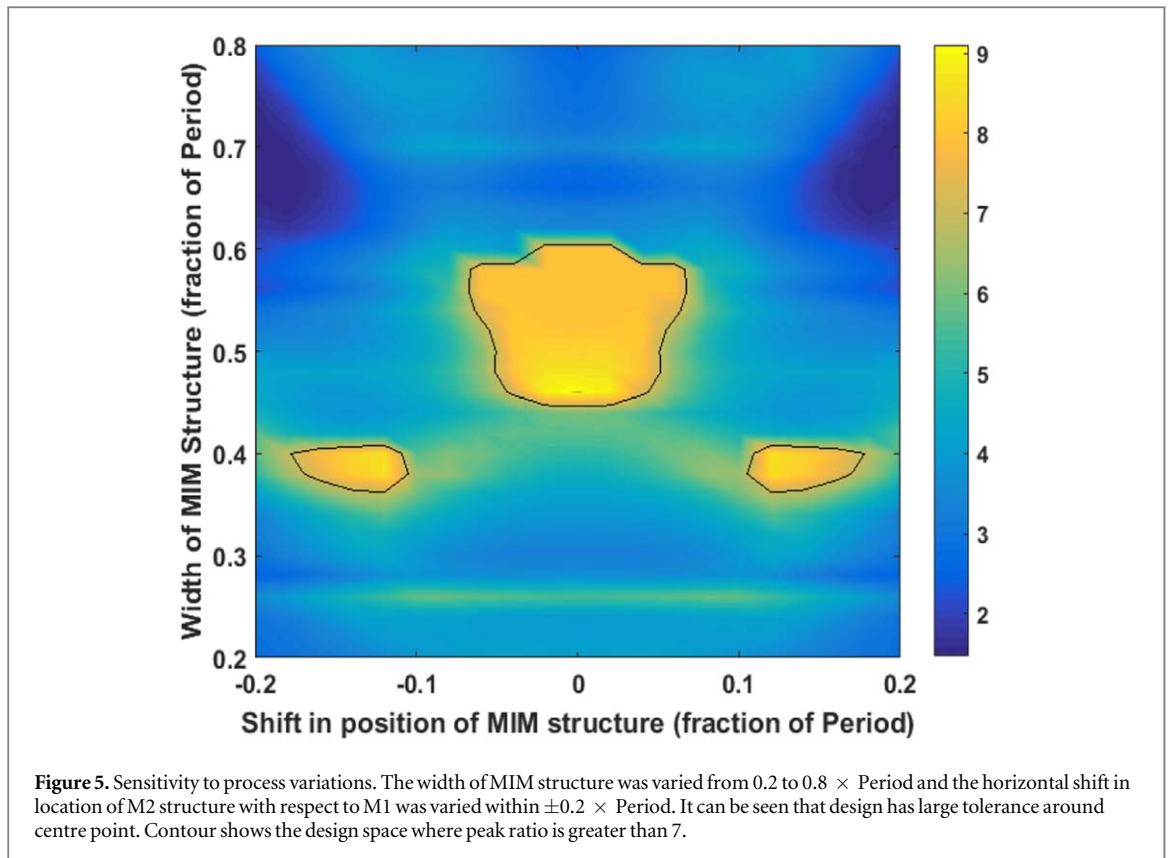
on M2) are asymmetric. The polarity of real part of E-field are in opposite direction at the ends. Comparing figures 4(a) and (c) we can clearly see that E-field beyond the filter structure (in +z direction) is much weaker in filter with MIM structure. This numerical analysis proves the basis for cancellation of the RA peak. Now from the far field point of view there are two subwavelength gratings with the same periodicity such that field radiated from one grating is 180° out of phase to that from the other one. By assuming these scattered fields are isotropic radiations and projecting them to a far field plane, we can easily compute the total intensity as function of space. Due to non-harmonic field pattern this can only be done in numerical fashion. Based on numerical simulation at 5 um away from the grating, the integral of the electric field is close to zero at 425 nm wavelength in proposed structure. At main transmission peak however, the shorter M2 structure is less than half the wavelength and hence cannot resonate and hence there is no significant effect in desired transmission peak.

In practical consideration, the proposed scheme needs to work under possible variation during fabrication. One of the most critical considerations is the effect of width of M2. Hence, the proposed structure was simulated for various widths/period ratios. The results are presented in figure 5.

It is clearly evident that within 0.45–0.6 width/period ratio, the extinction ratio is greater than 7. However, if the width variation is more, it significantly degrades the cancellation. In terms of practical issues during fabrication, ±7.5% variation of width translates to ±30 nm, which can be easily achieved in nano-lithography process. Now since the structure will require at least two lithography steps, the alignment requirement for the two lithography processes needs to be considered. So, a similar simulation with various horizontal shifts was done in RCWA and the combined results are presented in figure 5. Based on the simulation the performance gradually degrades as M2 position is shifted from the center position. For up to ±20 nm shift, the performance is still good in terms of suppression of RA peak. The extinction ratio is still higher than 7, which is significant compared to 2.2 in the filter without proposed modification.

In conclusion, a MIM plasmonic filter for suppressing RA was proposed. A thorough analysis and simulation was presented to describe the mechanism for suppression and sensitivity of the design to fabrication tolerances were evaluated through simulation. By using the proposed scheme, the spectral range ($\Delta\lambda$) of plasmonic filter array can be extended to at least $\lambda_{min}$ (the starting wavelength of the spectral range of interest) while achieving extinction ratio of 7.

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