Plane-wave Expansion based modelling of Cassegrain-type Reflective Objective

Lal Krishna A S[#], Jayanta Deka[#], Jyothsna K. M., Rabindra Biswas, Varun Raghunathan[*]
Department of Electrical Communication Engineering, Indian Institute of Science, Bengaluru 560012, India
*lalkrishna@iisc.ac.in, *varunr@iisc.ac.in*
[#] *These authors contributed equally to this paper*

Abstract

Cassegrain-type reflective objectives are widely utilized when performing high-resolution infrared optical micro-spectroscopy experiments. Experiments involving the mixing of two or more colors of photons, widely separated in wavelength, greatly benefit from such mirror-based objectives due to the aberration-free optics construction. However, this comes at the expense of a central obscuration for the excitation angles due to the positioning of the secondary mirror with respect to the primary mirror inside the objective. The effect of obscuration on the linear and non-linear response measured is important and has not been a subject of investigation. In this work, we utilize COMSOL Multiphysics's wave optics module to model and simulate the linear and non-linear optical responses from an amorphous-germanium (a-Ge) on quartz-based metasurface platform under mid-infrared wavelength illumination using a reflective objective of 13% central obscuration. The modelled linear transmission response of the refractive objective was in good agreement with the Gaussian-based finite area simulation results. Similarly, non-linear responses were studied using third-order sum frequency generation (TSFG) as the underlying non-linear phenomena. The simulated TSFG spectra were in good agreement with the experimental spectra. This modelling approach can be utilized to study optical responses from modified excitations in photonic applications.

Keywords: COMSOL Multiphysics, Cassegrain, reflective objectives, non-linear, third-order sum frequency generation, Electromagnetics, Gaussian, plane wave, Poynting vector, obscuration.

Introduction

Photonics applications utilize a variety of optics like lenses, mirrors, objectives, etc to achieve certain functionalities. From a ray optics point of view, we can model the response of such components using commercially available softwares [1,2]. However, to study certain linear and non-linear optical responses wave optics treatment is essential. There are a considerable amount of simulation platforms with the aforementioned capabilities [3,4]. Although a variety of optical components can be modelled using such software, there are special situations where electromagnetic modelling meets limitations. Modified excitation of the optical beam using Cassegrain-type reflective objectives [5] comes under such a category. They are widely utilized when performing high-resolution infrared optical micro-spectroscopy experiments. Conventional lens-based objectives often suffer from chromatic aberration and also result in absorption if utilized for broadband operation. Experiments involving the mixing of two or more colors of photons, widely separated in wavelength, greatly benefit from such mirror-based objectives due to the aberration-free optics construction. However, this comes at the expense of a central obscuration for the excitation angles due to the positioning of the secondary mirror with respect to the primary mirror inside the objective. Schematic diagrams comparing the conventional lens-based refractive objective and mirror-based Cassegrain-type reflective objective are shown in Figure. 1.

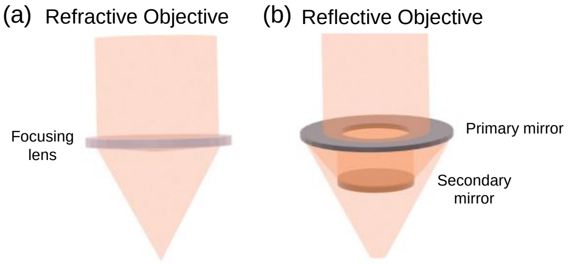

Figure. 1. Schematic of (a) conventional lens-based refractive objective and (b) mirror-based Cassegrain-type reflective objective.

From an experimental point of view, the effect of obscuration on the linear and non-linear response is important and has not been a subject of investigation. COMSOL Multiphysics's wave optics module is a powerful and versatile tool for studying both the linear and non-linear optical responses from different photonic structures including periodic gratings, and isolated structures of different geometries, over various material platforms. We have considered one-dimensional (1D) amorphous germanium (a-Ge) gratings on a quartz substrate as the metasurface platform to study the effect of obscuration in optical responses. A unique dual-step profile for the gratings, as shown in Figure. 2 is selected to introduce an asymmetry in the structure and facilitate the excitation of bound states in the continuum (BICs) [6], a special class of spectral resonances known for ultra-high quality factors resulting in the multi-fold enhancement of electric fields. The dimensions of the gratings are selectively designed to excite quas-BICs in the mid-infrared wavelength region [7].

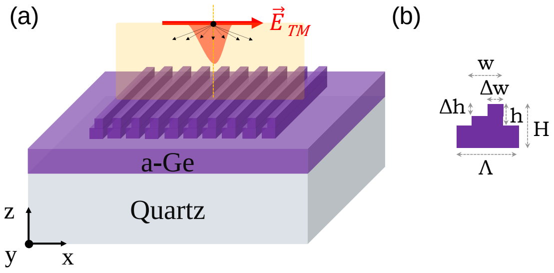

Figure. 2. (a) Dual-step grating geometry under study and (b) cross-sectional view

In this study, we have utilized a plane wave expansion-based (PWE) model to study the linear and non-linear optical responses from the dual-step gratings under the modified excitation from a reflective objective. Transmission spectra and third-order sum frequency generation (TSFG) respectively represented the linear and non-linear responses under consideration. Here a series of plane waves with suitable amplitude scaling were introduced and responses were coherently summed to model the responses under Gaussian (conventional refractive objective) and modified Gaussian excitations (reflective objective). A good agreement between the modelled and experimental responses was observed.

Plane wave expansion model

The main principle behind the model is to represent the modified Gaussian excitation using a series of plane waves with scaled intensitiesThe PWE algorithm is summarized in the Figure. 3. Plane waves at specific wavelengths were iterated over an angular range of interest (decided based on the type of objective and NA). he model takes focusing optics parameters as the unput to decide the bounds over which the series of simulations are performed. Namely numerical aperture and obscuration angle are the two important parameters, related to the objective used. In our work we utilized a 0.65 NA reflective objective with 13% central obscuration. The range of angle of incidences can be calculated from the NA of the objective under consideration. For example, an NA of 0.65 corresponds to 0 to 40 degrees of incidence angles, which will be restricted to 15 to 40 degrees with 13% obscuration. We considered a series of plane wave incidences in the angular range decided based on the objective and with periodic boundary conditions (as used in general for plane wave excitation) are considered along the X and Y directions (see Figure. 2). In a way we are modelling the Gaussian excitation using a series of plane waves with scaled amplitudes.

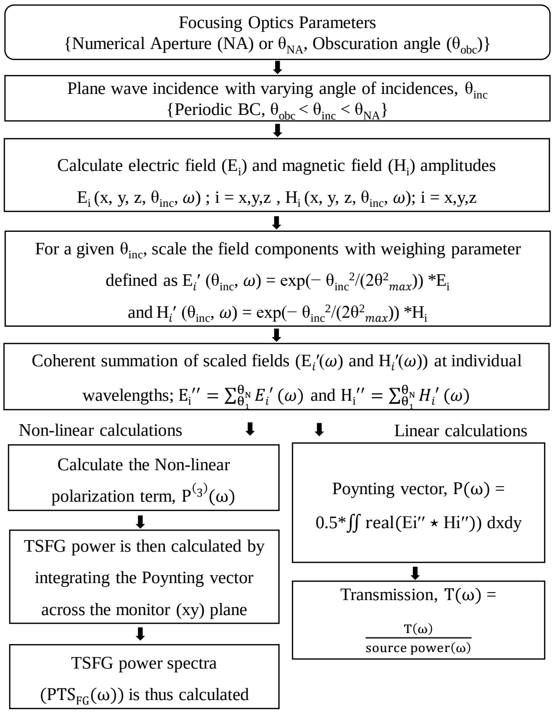

Figure. 3. Flow chart detailing the planewave expansion (PWE) based model

Here we utilized a scaling factor, as a function of angle of incidence (θ_{inc}). Thus the source power is scaled to match the Gaussian profile and corresponding fields (both electric and magnetic) components are recorded. A coherent summation of field components resulted in the calculation of overall effect of angles at a particular wavelength. At this stage, the effect of obscuration can be included by simply considering the angles of interest and neglecting the rest. This would lead to a generalized model where any arbitrary excitation conditions can be mimicked by adjusting the parameters. Once the field components, coherently summed are calculated over the entire spectrum of interest, linear and non-linear responses can be determined. For e.g. linear transmission spectra can be determined from the Poynting vector calculation. Non-linear optical responses like TSFG power spectra can be calculated by allowing the modified fields to propagate through the non-linear optical medium (a-Ge here). Third-order non-linear polarization of the layer is an important parameter and can be incorporated in the simulation software. We validated the model by comparing the linear and non-linear responses from the dual-step aGe gratings when excitation using reflective objective (supporting 15 to 40 degrees) and a conventional refractive objective without obscuration (supporting 0 to 40 degrees), as discussed in the following sections.

COMSOL based simulations

COMSOL Multiphysics's wave optics module was utilized to set up the simulation model. Fugure. 4 shows the COMSOL graphics with the geometry under consideration. Here an input port (source) for exciting the plane wave and output port for calculating the transmission were defined. Different regions were identified with corresponding refractive indices and material properties. Parameters of interests like wavelength, NA, incidence angles, dimenisons etc, were defined in the parameter section. Suitable boundary conditions (periodic along X, Y and perfectly matched layer (PML) along Z) were also defined.

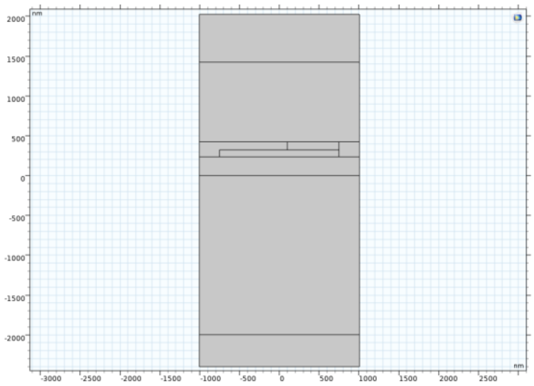

Figure. 4. COMSOL graphics showing the device geometry

By using the method section of COMSOL, a script function was defined to sequentially run the simulations iterated over all the angle of incidences and wavelengths. We used the wave optics physics to add the electromagnetic waves frequency domain (ewfd) module and thereby study the optical responses from the mid-infrared (signal wavelength) and a separate ewfd module for the 1040 nm (pump) wavelength. Similarly, a separate module dealing with the TSFG response was also used to study the non-linear response of the dual-step structures. Suitable monitors were also utilized to study the fields. Electric field components and the non-linear polarization (log scale) corresponding to the mid-infrared wavelength of 3.3 μm are shown in Figure. 5. The non-linear polarization term is defined as

$$P^{(3)}_{ijkl} = \varepsilon_0 \chi^{(3)}_{ijkl} E_j \, E_k \, E_l \tag{1}$$

Where ε_0 = permittivity of the free space (~ 8.854e-12 F/m), $\chi^{(3)}_{ijkl}$ = third-order non-linear optical susceptibility of the a-Ge layer (m^2/V^2), E_j, E_k = Electric field magnitude corresponding to signal photon, E_l = Electric field magnitude corresponding to pump photon

Here the dominant field components are shown to capture the distribution of energy within the structures. Since the a-Ge grating structure is responsible for the dominant non-linear responses, non-linear polarization is evidently concentrated within the dual-step gratings and the resonance enhancement of electric fields eventually lead to stronger TSFG response from the gratings.

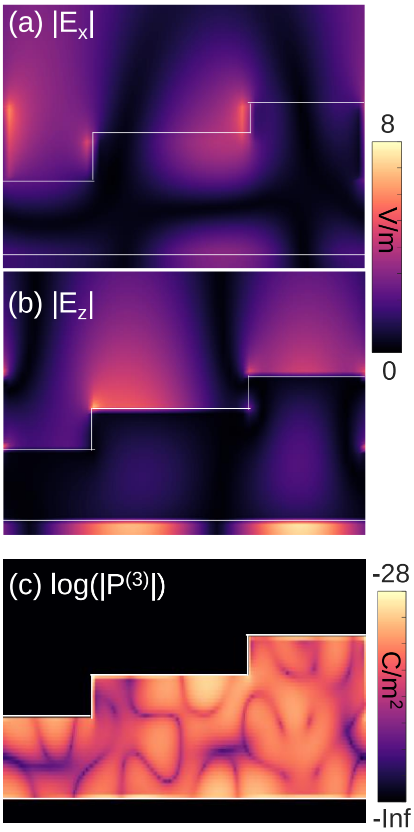

Figure. 5. Absolute value plots of electric field amplitudes for (a) x- and (b) z-components, and (c) third-order non-linear polarization term P(3) (log-scale)

Experimental results

The PWE model was used to calculate the linear and non-linear optical responses considering the experimental parameters. Non-linear microscopy set-up was used to study the TSFG responses as a function of signal wavelengths. Validation of the model was performed by comparing the responses of reflective objective (supporting 15 to 40 degrees) and a conventional refractive objective without obscuration (supporting 0 to 40 degrees). We then compared the results with the experimental TSFG spectra. The results are summarized in the Figure. 6. The modelled linear transmission response of the refractive objective was in good agreement with the Gaussian based finite area simulation results. A blue-shift of ~ 300 nm in the spectral resonance was found due to the effect of obscuration. Similarly, the TSFG response as a function of mid-infrared excitation wavelength peaked around ~ 2.9 µm, in contrast to the q-BIC spectral position of ~ 3.2 µm, as predicted by the model.

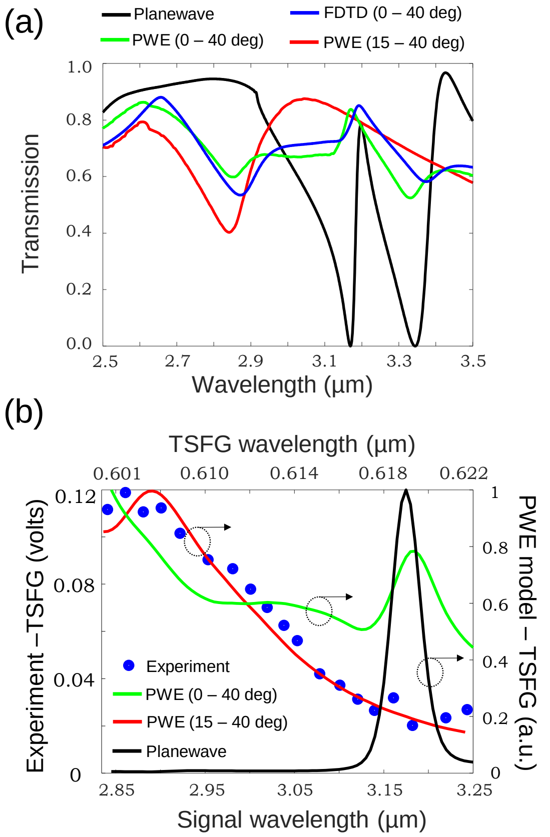

Figure. 6. (a) Simulated transmission spectra for; infinitely periodic gratings with plane-wave incidence (plane wave), finite area gratings with Gaussian excitation (FDTD (0 - 40 deg)), PWE-based modeling of Gaussian excitation (PWE (0 - 40 deg)) and gaussian excitation with obscuration (PWE (15 - 40 deg)), (b) PWE based modeling of TSFG signals under plane wave incidence, gaussian excitation (0 - 40 deg) and gaussian excitation with obscuration (15 - 40 deg) in comparison to the TSFG experiment data points.

Conclusions

We developed a plane-wave expansion based simulation model and utilized a non-linear optical phenonemenon of third-order sum frequency generation (TSFG) to validate the same. We found the proposed model as a promising method to study and predict both the linear and non-linear responses with different excitation conditions. In particular, mirror based reflective objectives utilized in non-linear signal mixing experiments for their wider transparency window and responses modified with obscuration can be modelled effectively with the proposed model. This approach to modelling the linear and nonlinear response from photonic structures of interest can potentially offer major advantages like enabling the modelling of source excitation with any arbitrary amplitude or phase distribution and can also bring down the memory requirement and computational cost.

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