Light Manipulation with Si Mesoscale Structures for Applications in IR Photodetector and Photoemitter Arrays

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Abstract — **Si anisotropic wet etching is applied to fabricate massive parallel microstructure arrays with novel optical properties. They can be used for enhancing light-concentration properties of mid-IR and long-IR focal plane arrays (FPAs), and for beam-shaping properties of IRLED arrays used in Infrared Scene Projectors (IRSPs).**

Keywords— silicon photonics, anisotropic etching, infrared photodetectors, light-emitting diodes, infrared projectors

I. Introduction

Over the last few years, we suggested that Si anisotropic wet etching could serve as an innovative technique for creating light concentrators utilized in mid-wave infrared (MWIR) focal plane arrays (FPAs) [1-3]. The technology was primarily restricted to the microelectromechanical (MEMS) field, with limited optical applications. However, this approach facilitates the parallel fabrication of large-scale micropyramidal arrays with smooth sidewall surfaces, which are highly attractive for optical applications. In our prior research, the examination of optical properties was restricted to a single microcone geometry, with a larger base of 14 µm and the smaller base of 4 µm [3]. It raised a question regarding the impact of the micropyramid's geometrical parameters on the optical properties of such arrays, including the role of light diffraction on such grating structures. In contrast, in the photodetector application, each micropyramid needs to focus light onto its own detector, and the estimation of the intensity enhancement factors (IEFs) on the detectors is necessary [4]. In the latter case, the incident light is usually incoherent, and the influence of diffraction effects is less significant. In addition, due to reciprocity principle, the same arrays can be used for beam shaping in IRLED arrays used in Infrared Scene Projectors (IRSPs).

This work is devoted to numerical modeling of the optical properties of such arrays in detector applications. We plan to study their emitter applications in our future work. Our methodology is based on the diffraction properties of such arrays, resulting in the Talbot effect which can be reproduced using periodical boundary conditions (BC). On the other hand, the light-concentrating properties of individual micropyramids manifest themselves due to narrow beams called "photonic nanojets", which emerge near the truncated micropyramid tops. These can be studied using perfectly matched layer (PML) BCs.

II. Simulation and Experimental Results

A. Role of the Boundary Conditions (BCs)

Computer simulations were conducted using Lumerical's Finite-difference time-domain (FDTD) software. As an object we used a truncated Si micropyramid with a refractive index of n = 3.5, and the 54.7° slope of the sidewall surface. Other geometrical parameters of micropyramids were varied. The source of plane waves was embedded in a Si wafer.

The difference between two types of BCs is illustrated in Fig.1. Choosing periodic BCs leads to periodical intensity modulation reminiscent of the Talbot effect [5], as demonstrated on the left side of Fig. 1. In contrast, the PML BCs means that EM waves that reach the computational boundary can escape the region. Therefore, this kind of BCs characterizes the performance of individual micropyramids, disregarding the effects of diffraction and interference from neighboring structures. Consequently, the calculations exhibit a solitary EM peak – photonic nanojet, as depicted in the right-hand section of Fig. 1. The latter case is representative of the practical use of micropyramids integrated with photodetectors.

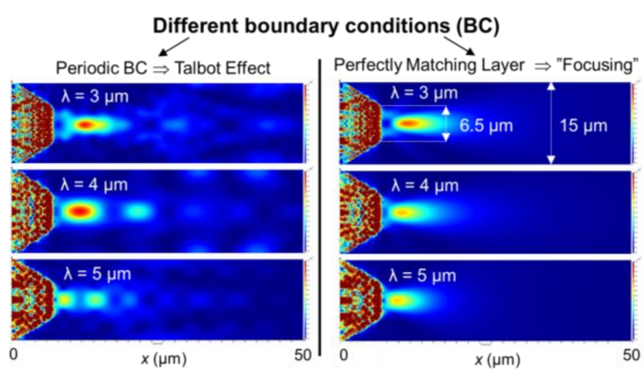

Fig. 1. EM field distributions for Si micropyramids (n=3.5) with a large base of 15 µm and a small base of 6.5 µm were computed at normal incidence. With periodic BCs, the Talbot effect caused multiple EM peaks. Conversely, with PML BCs, a standalone "photonic nanojet" was observed.

B. Talbot Effect Modeling & Experiment: Periodic BC

The relationship between calculated EM maps and the period of the array (A), corresponding to the size of the micropyramid's large base, were examined to demonstrate that the EM peaks observed using periodic BC resulted from the Talbot effect. The theory behind the Talbot effect states the spacing between adjacent EM maxima is the Talbot length (x_T) [5]:

$$x_T = \lambda/[1 - (1 - \lambda^2/A^2)^{1/2}]. \quad (1)$$

The simulation results indicate that the spacing between adjacent EM peaks shown on the left side of Fig.1 adheres closely to the Talbot length predicted by Eq. (1), providing evidence that the peaks arise from the Talbot effect.

In the experimental investigation, the Talbot effect was explored by utilizing back-side illumination with a $\lambda = 2.96$ µm Er:YAG laser slightly focused to a spot size of ~0.5 mm. The transverse intensity profiles at various imaging planes were captured with a MWIR Spiricon beam profiler by using a Ge lens shifted along the optical axis (x) with a micrometer. The brightest image was observed at the focusing plane near the tops of the micropyramids, as predicted by the numerical modeling results on the left part of Fig. 1. The separation between experimentally observed peaks agreed with Eq. (1), which confirms the Talbot effect nature of the optical properties observed under coherent illumination.

C. Light Concentrator Modeling: Perfectly Matched Layer BC

In contrast, the use of PML BCs eliminates the grating properties and enables the study of the light concentration properties of individual micropyramids. The power can be directed towards the smaller base, similar to microcones [3, 4].

The field monitor was positioned at the photonic nanojet's maximal intensity location. IEF was defined as a ratio of the peak intensity to the uniform intensity which would be detected without micropyramidal concentrator. Fig. 2(b) indicates that the IEF and FWHM of the photonic nanojets are dependent on the size of the smaller base, demonstrating that the locations of the IEF maxima are linked to the FWHM minima. This result is predictable because the total photon flux is conserved and it is proportional to (Peak IEF) × (FWHM)^2. With a fairly large size of the smaller base equal to $3.7\lambda = 11.1$ µm, the maximum IEF~7 can be attained with FWHM of photonic nanojet $\sim\lambda = 3$ µm.

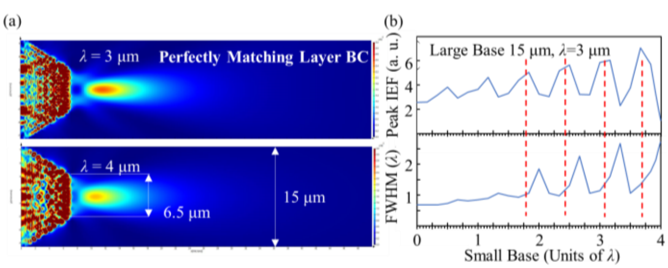

Fig. 2. (a) PML BC EM field distributions depicting photonic nanojets calculated for a micropyramid with small base size 6.5 µm and large base size 15 µm at λ=3 and 4 µm. (b) Plots showing the photonic nanojet's dependency on the peak IEF and FWHM relationship as well as the micropyramid's small base size in wavelength units for $\lambda = 3$ µm.

These findings are useful because such micropyramids are easy to manufacture by anisotropic wet etching of Si and they can be easily integrated with different front-illuminated photodetectors. Despite our efforts to optimize the system, the process remains incomplete as we did not modify the pitch of the array. We intend to conduct a complete optimization analysis by varying the pitch of the array in our forthcoming research.

III. Conclusion

The study encompasses three main aspects: (i) numerical modeling with periodic BCs to theoretically describe the Talbot effect in micropyramidal arrays, (ii) the Talbot effect in micropyramidal arrays was observed experimentally, and (iii) the IEFs provided by micropyramids using PML BCs were assessed by numerical modeling. It is shown that the experimentally observed Talbot images are in good agreement with the theoretical predictions. Furthermore, the research reveals that the individual micropyramids produce photonic jets with wavelength-scale dimensions. Besides applications in IR photodetector FPAs the proposed structures can be used in emitter applications such as IRLED arrays. Some properties can be predicted based on a reciprocity principle. As an example, one can suggest that the IRSPs with high extraction efficiency and with controllable emission directionality can be designed based on integration with the micropyramidal arrays. It should be noted, however, that the reciprocity principle is applicable only to the same optical modes [6], so that the full analysis of emitter applications would require modeling considering directional properties of the local emitters.

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