Wave analysis of bio-inspired eye structures for infrared detection

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***Abstract* – The dynamics of nature and the science of bioinspired technology can provide life vision for technologies. In this study, wave analyses were performed of bioinspired compound eyes to see the practicability of designing novel infrared detectors. By means of finite-difference time-domain numerical calculations, a large operational bandwidth, ranging from 3.0-12.0 µm, together with a high transmission efficiency over 85% have been achieved. The present study may provide useful guidance into the understanding of electromagnetic wave phenomenon inside bioinspired photodetectors.**

I. Introduction

The dynamics of nature and the science of biomimicry can give humans insight for technologies to ease our everyday life. The materials in nature have the desired properties such as durability, flexibility, and lightness. Natural sight structures of small invertebrates, i.e., compound eyes of bees or flies, are perfectly designed to have enough visual information about their surroundings without overloading the brain with unnecessary image processing. Although these compound eyes are composed of small optical units, they can detect wide-angled electromagnetic waves, their reflection rate is small and absorption rate is higher at the photoreceptor site. Mimicking such a natural imaging system in real word application will not be straightforward. Besides, high-resolution cases increase the overall cost of the detectors [1,2]. The interaction of light with the human eye or other eye structures in nature is generally determined by the ray analysis. Light's wave property is not taken into consideration in these kinds of analysis, and because of this, some properties such as the amount of energy at the focal point or at the photoreceptors, the losses caused by reflection at the interfaces, cross-talks between each ommatidium and absorption cannot be fully examined.

In this study, we perform full-wave numerical study on an infrared detector, whose optogeometric and material properties were extracted from the eye structure of honeybees. We show that the superior vision ability of honeybees can be exploited to build novel broadband infrared detectors with low losses.

II. Methodology

Finite-Difference Time-Domain (FDTD) method is a popular computational method and preferred in electromagnetic problem solving. In this study, we incorporate FDTD method for the wave analysis of compound eye in order to see the feasibility of designing novel infrared detectors (see Fig. 1). To obtain the maximum resolving power at the mid- and far-infrared wavelengths, the structural dimensions were determined by the well-known spatial resolution equation $_{d}$=1.22 /d, where is wavelength and d is the diameter of the lens' aperture [3,4]. The numerically calculated spatial intensity distribution is given in Fig. 2. One can infer from this figure that two distinct energy localization appear inside the crystalline cone (CC) and the rhabdom. While the first localization originates from the focusing behaviour caused by the cuticular lens, the latter arises due to the spatial wave compression and guiding inside the rhabdom.

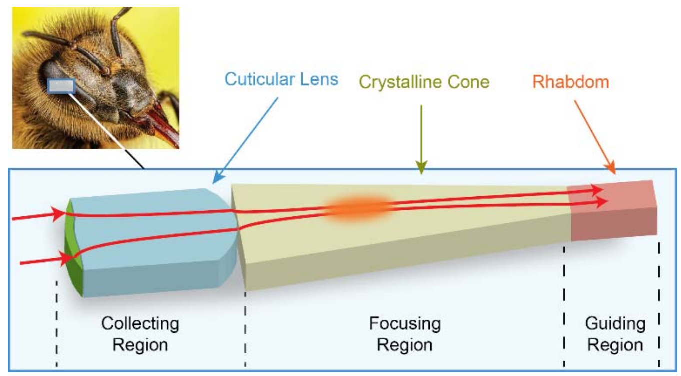

Fig. 1 Schematic description of the bioinspired infrared detector. The red lines denote the ray trajectories of the propagating waves.

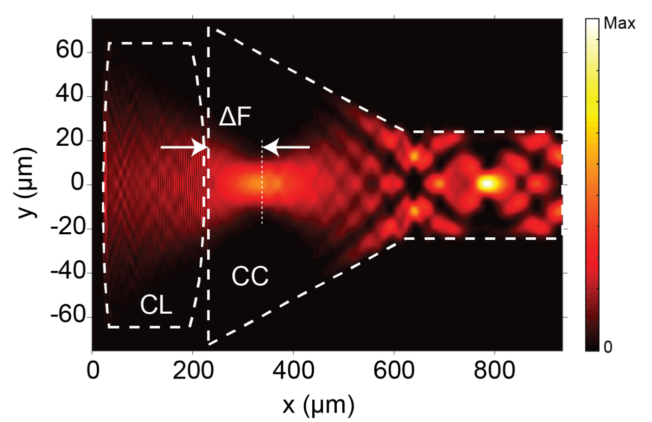

Fig. 2 Spatial electric field intensity for the operational wavelength equal to 12 µm is given. The white dashed lines outline the structure, which consists of cuticular lens (CL), crystalline cone (CC) and rhabdom.

Furthermore, it has been found that the energy localization inside the rhabdom is well-confined and can be guided over large distances. On the other hand, the longitudinal position of the focal point inside the CC has been found to exhibit strong wavelength dependency, as shown in Fig. 3.

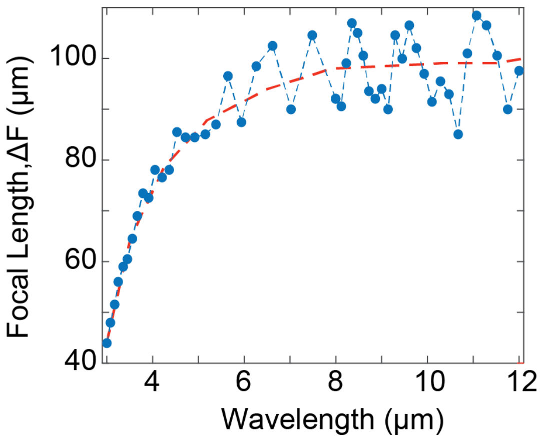

Fig. 3 The variation of the focal length with the operational wavelength.

Moreover, as shown in Fig. 4 the proposed structure also shows high transmissive characteristics over a broad wavelength range. It is worth noticing that the transmission is almost wavelength independent, which indicates a potentially uniform detection efficiency. Furthermore, as can be also seen from this figure, the reflection is below 10%, which eliminates the need of any anti-reflection surface.

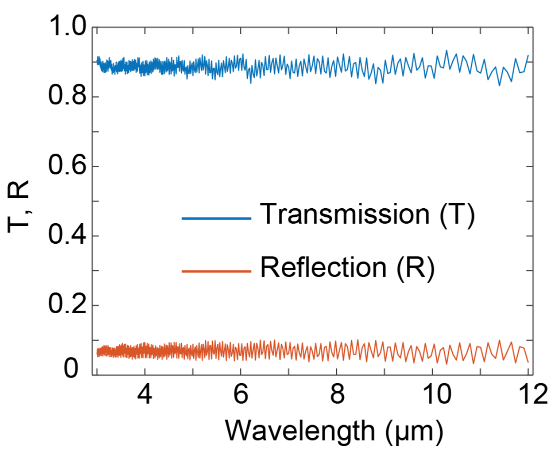

Fig. 4 Superimposed transmission and reflection spectra are given.

The numerical results verify the potential usage of the proposed design as infrared detector. As a future step, absorbing materials may be implemented inside the guiding region, to obtain the overall absorption efficiency. Moreover, electrical simulations may be performed to obtain charge collection due to electron-hole generations.

III. Conclusions

In summary, this study aims to design unique infrared detectors based on bio-inspired optics. Infrared detectors are designed to perceive the infrared radiation from objects and have been used in defence industry intensely in various applications like target acquisition, surveillance, fire control, and missile seeker.

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