Guided-mode resonance based multicolor germanium infrared photodetector

Y. A. Yılmaz[1]*, Z. Hayran[1], F. Yıldız[1,2], T. O. Kılınç[1,2], C. Karabacak[1], E. Bor[1,3], H. Kurt[1]
[1]Department of Electrical and Electronics Engineering, TOBB University of Economics and Technology, Ankara, 06560, Turkey
[2]Roketsan Missiles Industries Inc., Ankara, 06780, Turkey
[3]Department of Electrical and Electronics Engineering, TED University, Ankara, 06420, Turkey
*yayilmaz@etu.edu.tr

***Abstract* – A compact low-cost multicolor germanium (Ge) infrared photodetector is designed by utilizing the guided-mode resonance condition of a one-dimensional grating with adiabatically tuned (or so-called chirped) in-plane periodicity. It is shown numerically that the resonance phenomenon is accompanied by a spectral splitting, as every wavevector component is matched with different instantaneous local in-plane periods. In result, the proposed photodetector enables multi-wavelength photon absorption up to 61% efficiency and an ideal responsivity up to 0.63 A/W over a 70 nm bandwidth, while maintaining a very small active region of 0.413 μm². The reported results provide a very valuable insight into highly miniaturized ultra-compact multicolor photodetection schemes.**

I. INTRODUCTION

The ideal photodetector would allow highly efficient photon harvesting, while at the same time resolving the individual wavelengths of an incident radiation. In this regard, to meet both requirements, much research effort has been directed towards nanostructures supporting specific resonance phenomena [1]. For instance, a critically coupled Ge photodetector under vertical illumination at 1.31 μm wavelength is presented [2]. While a metallic reflector is utilized as the back-side mirror of the detector, a Bragg reflector functions as the front side mirror of it. However, such single resonance based photodetectors usually perform in a monochromatic manner, i.e. they only detect at a narrow wavelength region. It would be highly desirable to extend such resonance effects to several wavelength ranges (see Fig.1). In this sense, for instance, a photodetector array which consists of InGaAs and Si has been designed to absorb different wavelengths or colors of the visible and infrared spectrum [3], where a Si layer is responsible for detecting wavelengths up to 1.1 μm and an InGaAs layer is in charge of detecting wavelengths up to 1.68 μm. However, the integration of photosensitive layers made from different material might hamper any mass-production attempt and would increase the overall manufacturing cost. A more feasible and cost-efficient approach would be to integrate multiple active layers made from the same material into a single configuration.

In this study, we propose a multicolor Ge photodetector based on a guided-mode resonator (GMR) with chirped in-plane periodicity (see Fig. 2(b)). We show that the adiabatically tuned in-plane periodicity can lead to frequency sensitive, strong photon localizations. We, then, further reveal that the localized modes can result in strong photon absorption by incorporating Ge active regions inside the center stripe. We should note that a chirped GMR was proposed recently [4] for bio-sensor applications. In this proposed configuration, the filling ratio was modified by changing the thickness of the grating step-wise. In this paper, on the other hand, we present the design of a GMR, where the thickness of the grating is constant and only the distance between each grating is modified. In this way, the fabrication requirements of the proposed device are expected to become less demanding, as the stripes do not require any additional structural alteration and can be easily manufactured by utilizing e.g. various electron beam lithography or nanoimprint lithography techniques.

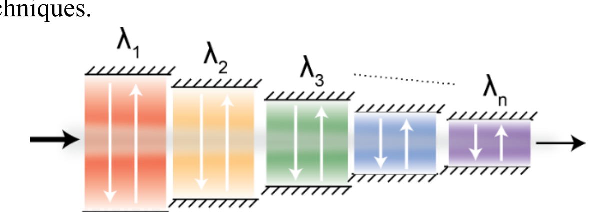

Fig. 1 Main idea of the proposal is shown. A cascade of optical resonators with varying frequencies can yield multicolor light localizations.

II. METHODOLOGY

The proposed configuration consists of 11 silicon (Si) rectangular stripes arranged in a radial manner (see Fig. 2(b)). The width (w) and length (L) of the Si stripes are equal to 0.765 μm and 9 μm, respectively. As shown in Fig. 2(b), each stripe deviates from the propagation x- direction by a specific angle, so that the instantaneous periodicity along the transverse y- direction remains constant and is gradually varied along the x- propagation direction. The angle variation that satisfies these conditions has been analytically obtained as in Eq. 1, where p_1 (= 0.9 μm) and p_2 (= 1.2 μm) are the transverse periods at the output and input of the structure, respectively; and n is the index of each stripe (0 for the center stripe, negative and positive values for stripes at the lower and upper half, respectively).

$$\theta_n = \tan^{-1}\left[\frac{n(p_2 - p_1)}{L}\right] \quad n = -5,-4\ldots4,5 \qquad (1)$$

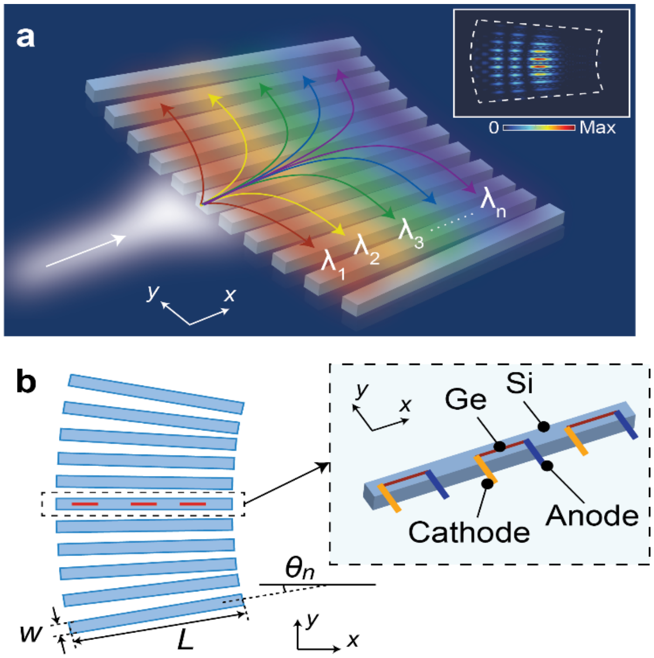

Fig. 2 (a) The adiabatically tuned in-plane periodicity of the proposed configuration provides spatial spectrum splitting accompanied by guided-mode resonance based high photon confinement. The upper right inset shows the numerically calculated resonance effect. (b) The schematic description is shown. The right inset depicts the zoomed view of the center stripe, which contains the Ge active regions.

To verify the operational principle, numerical analyses are conducted using the finite-difference time-domain method (FDTD) [5]. Perfectly matched layers are used to terminate the simulation boundaries and to reduce the computational time, the simulations were performed in a 2D grid. However, to fully account for the effective index change induced by a finite stripe height, a full 3D analysis is required (though the physical principle of the proposal will remain unchanged). A broadband source with transverse magnetic (TM) polarization (electric field is perpendicular to the plane) is used to excite the structure. The upper right inset in Fig. 2(a) depicts the steady state electric field intensity for the operational wavelength equal to 1.42 µm. One can clearly validate from this figure that the incident radiation becomes localized inside the chirped structure, which originates from the wavevector match of the operational frequency and the instantaneous local periodicity of the GMR.

Ge active regions (Ge-1, Ge-2, Ge-3), with spatial dimensions of 100x1500 nm, 100x1500 nm and 75x1500 nm in the *y*- and *x*- directions, respectively, have been implemented inside the center stripe, as shown in Fig. 2(b). The numerically calculated absorption spectra for all three Ge regions are superimposed in Fig. 3(b), whereas the free space absorption of Ge is given in Fig. 3(a). It follows from these figures that the absorption of Ge is enhanced at various wavelengths up to 60 times. Furthermore, Fig. 3(c) shows the responsivity spectra calculated for the same Ge regions under ideal conditions; this is to say that each absorbed photon is assumed to generate one electron-hole pair. This figure evidences the frequency sensitive photocurrent generation of 0.31-0.63 A per unit optical power, over a 70 nm bandwidth.

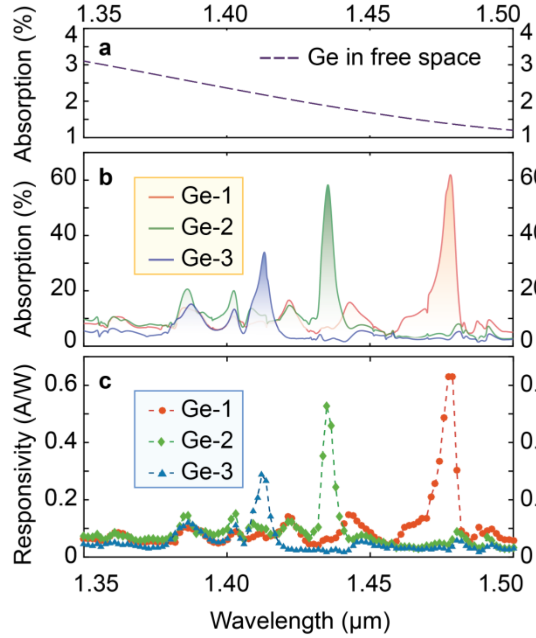

Fig. 3 (a) Absorption spectra of a 100-nm-thick Ge in free space. Superimposed (b) absorption and (c) responsivity spectra for Ge placed at a distance of 700 nm (Ge-1), 5050 nm (Ge-2) and 7130 nm (Ge-3) with respect to the input of the structure.

III. Conclusions

In conclusion, we propose the design of a GMR based multicolor Ge infrared photodetector. The designed photodetector exhibits a responsivity between 0.29-0.63 A/W for various wavelengths. Our design represents a feasible approach for photodetection applications with its compact size, small active region and low manufacturing cost.

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