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Abstract. The spectral discrimination function of uncooled infrared (IR) sensors has significant advantages for applications such as fire detection, gas analysis, and biological analysis. We have previously demonstrated wavelength-selective uncooled IR sensors using two-dimensional plasmonic absorbers (2-D PLAs) over a wide range spanning the middle- and long-wavelength IR regions. 2-D PLAs are highly promising in terms of practical application due to the ease of fabrication and robustness for structural fluctuations. However, dual-band operation based on this concept has not yet been investigated, even though the ability to absorb in two different wavelength bands is extremely important for object recognition. Thus, a dual-band uncooled IR sensor was developed that employs Fano resonance in the plasmonic structures. To achieve dual-band detection, asymmetric periods in the orthogonal x- and y-directions were introduced into 2-D PLAs. Theoretical investigations predicted an asymmetric absorbance line shape dependent on the polarization attributed to Fano resonance. The spectral responsivity of the developed sensor demonstrated that selective detection occurred in two different wavelength bands due to polarization-dependent Fano resonance. The results obtained in this study will be applicable to the development of advanced sensors capable of multiband detection in the IR region.

Keywords: Fano resonance; plasmonics; metamaterial; uncooled infrared sensors; dual-band.

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1 Introduction
There has been growing interest in uncooled infrared (IR) sensors1 in both industry and the field of applied physics.2 Typical uncooled IR sensors can detect information such as the average radiant intensity, position, and shape of an object. If uncooled IR sensors could obtain wavelength information, then objects could be identified through their radiation spectrum.3 Wavelength-selectivity in IR sensors could also lead to additional applications, including gas analysis, fire detection, hazardous materials recognition, and ultimately multicolor information. However, there has been serious difficulty to date in the construction of pixel-array formats with different detection wavelengths using typical wavelength-selective methods such as filters4,7 or optical resonant cavities.8 Additional optical attachments such as filters lead to complicated systems, which in turn leads to higher costs and a degeneration of the wavelength selectivity because the filters themselves emit IR radiation. Our group has developed advanced functional uncooled IR sensors with wavelength selectivity9,10 or multicolor imaging11 or polarization selectivity12,13 using plasmonics14,15 and metamaterials16,17 technologies to address this challenge and expand the potential applications. Absorbers that employ plasmonic and metamaterials have the advantage of enabling control over the absorption wavelength simply by varying the surface structural design. This has led to the fabrication of array formats with different detection wavelengths without the need for any filters or optical attachments, and thus the realization of low-cost and high-spectral selectivity systems.

Although we have realized single-mode operation, dual-band detection has not yet been investigated. Dual-band operation is particularly important with regard to analytical sensing applications, such as gas and material sensing as one potential use. Metal–insulator–metal absorbers18,19 are good candidates for this type of dual-band operation;20,21 however, such structures have restrictions in terms of the operation wavelength range22 and require precise control over the metal patch size23 for control of the absorption wavelength, which leads to complex manufacturing procedures and thus increases cost. On the other hand, two-dimensional plasmonic absorbers (2-D PLAs) have rich potential for a variety of practical applications due to their wide operational range in the middle- and long-wavelength IR regions, in addition to their simple fabrication processes and structural robustness.10,24,25

We have recently reported 2-D PLAs with asymmetric periods (2-D PLA-APs) that realize dual-band operation due to Fano resonance.26 Fano resonance is a phenomenon that involves interference between a discrete state and a continuum state.27,28 Recently, Fano resonance has been identified in various metallic photonic,29 plasmonic,30 and metamaterialic structures.31-33 However, the detailed effect of Fano resonance in 2-D PLA-APs for dual-band detection has not yet been reported. Here, we provide a detailed report on dual-band detection based on Fano resonance induced in the asymmetric geometry of 2-D PLA-APs.
2 Theoretical Design

Figure 1(a) shows a schematic illustration of a symmetric Au-based 2-D PLA. Figures 1(b) and 1(c) show the top views of 2-D PLAs with symmetric and asymmetric periods, respectively. Figure 1(d) shows the definition of the polarization angle (θ) for the incident electric wave (E). In this study, the incident angle was normal to the surface, considering practical applications. It should be noted that Figs. 1(b) and 1(c) show only four unit cells, where the periods \( p_x \) and \( p_y \) are defined in the x- and y-directions, along with the diameter, \( d \).

The \( p_x \), \( p_y \), and \( d \) values, and the depth of the dimples were set at 6.5, 4.0, 3.0, and 1.5 μm for both calculations and experimental trials, considering the resolution limit of the experimental instrumentation and for comparison with our previous studies. The absorption wavelength of symmetric 2-D PLAs maintains a single mode, is independent of the polarization, and is almost equal to the surface period, as demonstrated previously.\(^{10,12}\) The absorption properties of the 2-D PLA-AP were calculated using rigorous coupled wave analysis (RCWA). Figure 2 shows the absorbance spectra for nonpolarization and for \( \theta \) at 0 deg and 90 deg. The spectrum for nonpolarization was calculated using \( \theta \) at 45 deg, which can be obtained from the average of the spectra for \( \theta \) at 0 deg and 90 deg.

Figure 2 indicates that the strong polarization dependence is produced due to the symmetry-broken period structures. Two absorption peaks of approximately 40% and 50% are observed for nonpolarization, and of approximately 35% and 90% for \( \theta = 0 \) deg at approximately 4.0 and 6.5 μm, which almost correspond to \( p_x \) and \( p_y \), respectively. The asymmetric line shape of Fano resonance is evident in these spectra. In contrast, only a single and broad absorption peak of 50% is observed for \( \theta = 90 \) deg at around 4.0 μm, which corresponds to \( p_y \). These results indicate that dual-absorption peaks are produced due to the interference of the surface plasmon modes in the \( x \) and \( y \) period for \( \theta = 0 \) deg, while the single absorption peak for \( \theta = 90 \) deg
is attributed to the surface plasmon mode only in the y-direction. The surface plasmon wavelength in the x-direction is longer than that in the y-direction; therefore, these two resonances can interfere only for $\theta = 0$ deg. On the other hand, there is less interference of these two modes in the y-direction.

These properties were investigated in detail by applying the classical analogy of Fano resonance\textsuperscript{\textsuperscript{28}} to 2-D PLA-APs. The surface plasmon resonances in the x- and y-directions are the same in symmetric 2-D PLAs due to the symmetric geometry, whereas they are different in 2-D PLA-APs due to the asymmetric geometry, as shown in Fig. 2. Therefore, symmetric and asymmetric-period 2-D PLAs can be considered with respect to single and double oscillator models, as schematically shown in Figs. 3(a) and 3(c), and in 3(b) and 3(d), respectively.

$\omega_0$ is the natural frequency of the oscillator, which is defined by the mass and the spring constant in the absence of damping, and $\gamma_0$ is the frictional parameter. $\omega_1$ and $\omega_2$ are the natural frequencies of the oscillator for the x- and y-directions, $\gamma_1$ and $\gamma_2$ are the frictional parameters for the x- and y-directions, and $\nu_{12}$ is the coupling of the two oscillators. The oscillation amplitude $c(\omega)$ for the single oscillator and $c_1(\omega)$ and $c_2(\omega)$ for the double oscillator are described in Ref. 28, as follows:

\begin{equation}
|c(\omega)| = \frac{A}{\sqrt{(\omega_0^2 - \omega^2)^2 + \omega^2 \gamma_0^2}},
\end{equation}

\begin{equation}
|c_1(\omega)| = \frac{\omega_2^2 - \omega^2 + j\nu_{12}\omega}{(\omega_1^2 - \omega^2 + j\nu_{12}\omega)(\omega_2^2 - \omega^2 + j\nu_{12}\omega) - \nu_{12}^2} A_1,
\end{equation}

\begin{equation}
|c_2(\omega)| = \frac{\nu_{12}}{(\omega_1^2 - \omega^2 + j\nu_{12}\omega)(\omega_2^2 - \omega^2 + j\nu_{12}\omega) - \nu_{12}^2} A_1,
\end{equation}

where $A$ and $A_1$ are the constants. We focus on Eqs. (1) and (2) to investigate the asymmetric line shape. Figures 3(e) and 3(f) show the results calculated for Eqs. (1) and (2), respectively, using $\omega_0 = 1.0$ and $\gamma = 0.02$ in Eq. (1), and $\omega_1 = 0.8$, $\omega_2 = 1.2$, $\gamma_1 = 0.02$, $\gamma_2 = 0$, and $\nu_{12} = 0.2$ in Eq. (2). Both results were normalized according to the peak value.

These results show that the single and double oscillator models have single and dual resonance peaks, which correspond to the absorption properties of symmetric 2-D PLAs and 2-D PLA-APs, respectively. The single resonance peak as shown in Fig. 3(e) and the first resonance peak as shown in Fig. 3(f) were symmetric. These resonances can be fitted

![Fig. 4](https://www.spiedigitallibrary.org/journals/Optical-Engineering)

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with a Lorentzian function. The second resonance peak at \( \omega = 1.22 \) has an asymmetric line shape of Fano resonance, as shown in Fig. 3(f). This asymmetric line shape is produced because \( c_1(\omega) \) becomes zero at \( \omega = 1.2 \) and \( \gamma_2 = 0 \) close to the second resonance peak at \( \omega = 1.22 \), which distorted the line shape of the resonance peak. This destructive interference corresponds to the absorption spectra of 2-D PLA-APs, where the surface plasmon resonance in the \( x \)-direction destructively interferes with that in the \( y \)-direction near its peak wavelength, which produces the asymmetric line shape of the absorption spectrum shown in Fig. 2.

3 Sensor Fabrication

Microelectromechanical systems (MEMS)-based uncooled IR sensors (or thermopiles) based on 2-D PLA-APs were subsequently fabricated. Figure 4(a) summarizes the fabrication process. This procedure and the thermopile were the same as those reported in our previous studies, but in the present case the 2-D PLA-APs were patterned on the IR absorber area.

Each device was fabricated on a 6-in. silicon substrate using a standard complementary metal oxide semiconductor (CMOS) process. The thermocouples consisted of a series of p- and n-type poly-Si regions, the resistivity of which was controlled by ion implantation. An Al layer was formed under the absorber area as a backside reflective layer, and holes serving as cavities were formed via reactive-ion etching (RIE). A 1.5-\( \mu \)m-thick SiO\(_2\) layer was subsequently deposited as the absorber area. Following this, the 2-D PLA-AP structure was formed by RIE only on the SiO\(_2\) layer of the IR absorber area. Next, 50- and 250-nm-thick Cr and Au layers were deposited by sputtering, where the Cr layer acted as an adhesive between the SiO\(_2\) and Au layers. The 250-nm-thick Au layer was significantly thicker than the skin depth in the IR wavelength region, so the effects of the Cr and SiO\(_2\) layers beneath Au were negligible. The Cr/Au layers were selectively etched using a wet etchant to reveal the holes previously covered by the sputtered Cr/Au. Scanning electron microscopy (SEM) observations confirmed that the Cr/Au layers were uniformly coated. Each wafer was then diced into chips and the Si was anisotropically etched through the holes using tetramethylammonium hydroxide (TMAH). The TMAH was doped with Si so that the backside cavity Al layer was not etched. The cavity under the IR absorber area was then formed to complete the thermally isolated freestanding structure. Figures 4(b) and 4(c) present a schematic diagram of the thermopile with incorporated 2-D PLA-AP and an SEM image of the 2-D PLA-AP surface. The detector area (300 \( \times \) 200 \( \mu \)m) was surrounded by long thermal isolation legs to reduce thermal conductance.

4 Measurements and Discussion

The spectral responsivity of the sensor was measured for nonpolarized and polarized incident IR light using the same experimental setup as that used in our previous work. Narrow-band filters were used to select the evaluation wavelengths, and the spectral responsivities were calculated according to the use of a nonpolarized or polarized light source, which is advantageous considering the total sensor systems.

5 Conclusions

A dual-band uncooled IR sensor was successfully developed using a 2-D PLA-AP. RCWA simulations showed that two asymmetric absorption peaks were produced by the 2-D
PLA-AP, according to the polarization angle of the incident IR. These asymmetric absorption spectra were well explained by the classical analogy of Fano resonance. The asymmetric line shape of the Fano resonance in 2-D PLA-APs is attributed to the destructive interference of the asymmetric surface plasmon resonance of the x- and y-directions. An MEMS-based thermopile was fabricated with the 2-D PLA-AP. The spectral responsivity for nonpolarized and polarized incident light of the developed sensor with the 2-D PLA-AP confirmed that dual-band operation was realized due to the polarization-dependent Fano resonance. Dual-band operation such as that exhibited by this device should be applicable to various types of thermal IR sensors, such as bolometers and silicon-on-insulator (SOI) diodes. Thus, it is expected that the Fano resonance mode of the symmetry-broken plasmonic structures studied in this report will contribute to the development of advanced multimode uncooled IR sensors for various analysis applications.

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References


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