A novel scheme of optical readout based on thermo-optical cavity coupled plasmonic scattering for infrared detection

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Abstract
A novel scheme of optical readout based on thermo-optic cavity coupled plasmonic scattering for infrared imaging sensor is proposed to lessen the complex and bulky of existed systems using reflective or diffractive optical readout schemes. This new scheme readouts thermally-modulated back-scattering visible light signals of metallic nanostructures under large-angle dark field illumination. Numerical simulation is employed to reveal the mechanisms of large temperature sensitivity and low angular sensitivity of scattering, which is attributed to the thermal-optic effects of Fabry–Perot (F-P) microcavity coupled with local surface plasmon resonance (LSPR) generated from metallic nanostructures. The feasibility of the proposed scheme is demonstrated by preliminary experiments and optical measurements. Thermal-optic modulated scattering spectra have been obtained for 3.39 μm infrared illumination and a temperature sensitivity of 0.24 nm/℃ for 605 ~ 640 nm band has been reached. This scheme provides a new approach to develop compact and low cost infrared imaging systems.

Keywords Optical readout · Thermo-optic effect · Localized surface plasmon · Cavity-plasmon coupling · Infrared detector

1 Introduction

Uncooled thermal detectors including microbolometers, pyroelectric and thermopile detectors have achieved a wide range of applications in the fields of medical (Zhang et al. 2017), industrial (Georgouli et al. 2017), military (Pulpea 2015) and commercial fields (Shen et al. 2011) due to their low prices and small volumes. However, their lower performance compared with cooled infrared detectors carrying costly cryogenic coolers makes them rarely
applied in high-end imaging systems. Based on noise analysis, the ultimate performance level of uncooled thermal detectors was expected to be limited mostly by the readout noise (Kruse 1997). The readout circuit is used to measurement of electrical signals such as capacitance or resistance converted by thermal sensitive materials to complete the sensing of the temperature variation of the detector, so electrical conduction pathway is necessary for each detection unit, which inevitably induces readout circuit noise. Moreover, the metal materials in the readout circuit will increase the thermal conductivity of the detector and reduce the thermal isolation of the detector unit, which will eventually limit the temperature rise caused by infrared radiation. The current in the readout circuit also generates additional Joule heat, and then decrease in temperature rise which limits the accuracy of the detector. Since the change of the detector’s electrical signal due to temperature change is relatively small, large signal-to-noise ratio and gain of the readout circuit is required. Therefore, the design scheme and production cost of the readout circuit bring an important budget problem to be considered for uncooled thermal detectors.

In addition to the electrical readout approach, another way to achieve infrared detection and imaging is to use changes in the optical parameters of sensitive components to achieve an optical readout, for example, through changes in refractive index that affect the transmission or reflection characteristics of thermal-optic materials (Mohamed 2018). This method of using visible light readout can be achieved by specialized optical measurement equipment or even by using the human eye for observation (Watts et al. 2007). Other methods including MEMS bimorphs (Miao et al. 2007), photonic crystals (Exner et al. 2013), resonant waveguide grating (Enemuo et al. 2015), etc. So far, the use of optical readout has facilitated the emergence of various infrared sensor designs that convert infrared radiation into changes in visible light intensity for infrared detection and imaging. Compared to conventional uncooled thermal detectors, the optical readout technique was expected to significantly reduce the cost of the system by eliminating the limitations of cooling devices and readout circuits (Ostrower 2006) and eventually enhance the detection sensitivity. However, in practice, the performance of detectors with optical readout schemes was found to suffer from angular deviation of the reflector/absorber (Fu et al. 2016) or stray light influence as well as complicated and non-compact optics, which make the optical readout schemes no longer attractive.

In this work, we propose a novel scheme of optical readout of infrared radiation by using scattering spectra of metallic nanostructures with cavity-plasmon coupled modes. These coupled modes are generated from the hybridization of local surface plasmon resonances (LSPR) and Fabry–Perot (F-P) microcavity resonances and are modulated by thermo-optical effect of the microcavity. The coupled resonance modes are more sensitive with temperature than that of nanoparticles without microcavity resonances. Numerical simulations are used to reveal the coupling mechanisms, the insensitive properties of scattering spectra to the incident angle of visible light illumination and the temperature sensitivity of coupled structures. Preliminary experiments and optical measurements have been conducted to demonstrate the feasibility of this proposed scheme in infrared detection applications.

2 Structural design and numerical simulation

The quality factor of the sensing response of nanosensors based on the LSPR effect is greatly influenced by the resonance spectral width. In order to reduce the spectral width and improve the sensor sensitivity, a novel nanoparticle-coupled microcavity system is
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The main function of the F-P cavity is to modulate the light intensity when a light is incident on the cavity, and the intensity of its reflection spectral pattern can be expressed as

\[ I_R = \frac{4R \sin^2(\delta/2)}{T^2 + 4R \sin^2(\delta/2)} I_i \]  

(1)

where \( I_i \) and \( I_R \) are the incident and reflected light field intensity respectively; \( R \) and \( T \) are the reflectance and transmittance of the reflected end surfaces respectively; \( \delta \) is the phase difference between reflections.

When the phase difference \( \delta \) between any two adjacent beams satisfies the following relationship (2) and (3), the light intensities of the reflection spectrum have the maximum value and the minimum value respectively.

\[ \frac{4\pi n d}{\lambda_p} + \phi_0 = 2k\pi \]  

(2)

\[ \frac{4\pi n d}{\lambda_q} + \phi_0 = (2k + 1)\pi \]  

(3)

where \( \lambda_p \) and \( \lambda_q \) are the wavelengths at the reflection maxima and minima, respectively; \( n \) is the refractive index of the medium inside the cavity; \( d \) is the physical thickness of the intermediate cavity layer; \( \phi_0 \) is the initial phase of the F-P cavity; and \( k \) is an integer representing the order of the interference spectrum. The two high refractive index films in Fig. 1(a) cover the upper and lower layers of the low refractive index cavity and act as reflective end surfaces, where the incident light is reflected at the two boundaries to form standing waves. If the round-trip beam can obtain a phase shift of \( 2\pi \) after two reflections, a local cavity mode is formed inside the low refractive index cavity. When a single metallic nanoparticle is deposited directly on the surface of the microcavity, the cavity mode and the LSPR mode are coupled to each other at characteristic frequencies, forming a hybrid plasmonic super mode (Zhang et al. 2019).

**Fig. 1**  
(a) Structure diagram of nanoparticle coupling microcavity system with single Al nanoparticle.  
(b) Normalized back-scattering spectra of aluminum nanodisks on different substrates.
In order to simulate the effects of F-P cavity and aluminum substrate on the particle scattering characteristics, the high refractive index layer in the F-P cavity is set as a 100 nm TiO$_2$ film, the low refractive index layer is set as a 500 nm SiO$_2$ cavity, the aluminum nanodisk is 200 nm in diameter and 200 nm in height, and the aluminum substrate is a semi-infinite plane. The simulation analysis of the case of normal incidence is done by the time-domain finite-difference method. Figure 1(b) shows the back-scattering intensity of the aluminum nanodisk in different cases. It can be seen that the F-P cavity with aluminum substrate reduces the LSPR line-width by 79%, and doubles the scattering intensity. In order to elaborate the physical mechanism of the coupling process between the metallic nanoparticles and the F-P microcavity, the electric field strengths at typical resonance wavelength in the XoZ and YoZ cross sections for Al nanodisk on various substrates are plotted. As can be seen in Fig. 2, LSP resonances are generated at the top edge and bottom edge of the aluminum nanodisk on a surface parallel to the direction of the incident electric field vibration regardless of the substrate on which the aluminum particles are located. In the case where the particles are deposited on a bare glass substrate the electric field energy is not effectively coupled into the substrate, resulting in a relatively low back-scattering intensity and fewer LSPR patterns; in the case where the aluminum nanodisk is mode coupled to the F-P cavity, the two high refractive index layers of the F-P cavity at the resonance wavelength become reflective layers, and the round-trip beam is reflected twice in the plane perpendicular to the direction of the incident electric field vibration. The F-P cavity with an aluminum backing enhances the reflection of the incident light field, and the round-trip standing wave energy is more concentrated than that of the F-P cavity without an aluminum backing.

A qualitative analysis reveals that when individual metal nanoparticles are deposited directly on the microcavity surface, the F-P cavity mode and the LSPR mode are coupled to each other at the corresponding resonance frequencies and form a hybrid plasmonic mode. The metal nanoparticles effectively act as optical antennas during the coupling process, and the electric field energy of the incident light can be concentrated into the sub-wavelength volume of the metal surface and redirected to the F-P cavity mode by LSP resonance. During

Fig. 2  Cross-section of XoZ electric fields (a-c) and YoZ electric fields (d-f) of aluminum nanodisk when LSPR occurs at the same mode on Glass, FP cavity and FP cavity with the aluminum substrate, respectively
the internal circulation of the F-P cavity, part of the incident electric field energy is transferred from the cavity mode into the LSPR and then scattered from the nanoparticles, and the lowermost metal substrate effectively enhances the reflection effect of the F-P cavity. For this metallic nanoparticle microcavity coupling system, a significant reduction in the line-width of each individual resonance means that detection resolution limits can be significantly improved when using this resonant mode in sensing applications, substantially increasing sensor sensitivity.

The spectral positions of the metal particle resonances in Fig. 1b are investigated at large-angle oblique incidence, with the incidence angle \( \theta \) defined as the angle between the incident light and the plane normal to the bare F-P cavity and the relative wavelength shift defined as \( \Delta \lambda = [\lambda(\theta) - \lambda(89^\circ)]/\lambda(89^\circ) \). The results are shown in Fig. 3, where the relative wavelength shift of the bare F-P cavity reaches 11% at large-angle oblique incidence, while the nanoparticle cavity system resonance remains essentially at the same spectral position. Compared with the bare F-P cavity without particles, the spectral position of the metallic particle resonance is largely independent of the angle of incidence \((60^\circ < \theta < 90^\circ)\). This again suggests that the LSPR and cavity modes interact through multimodal coupling to form a hybrid plasmonic supermode with weak angular dependence. Under the large-angle oblique illumination, the back-scattering spectrum of nanostructures can be collected by a microscope objective, which has the advantage of high contrast as that of commonly used dark field microscopy.

We now consider the temperature sensitivity of the coupled system. When the ambient temperature changes, the thermal expansion effect of the microcavity and the thermo-optic effect of the medium in the microcavity will affect the thickness \( L \) of the microcavity and the refractive index \( n \). Therefore, the temperature can be sensed by observing the drift of the peak or valley wavelength of the spectrum measured. According to formula (2), a temperature response expression is obtained as:

\[
\frac{d\lambda_k}{dT} = \frac{2\pi}{k} \left( \frac{dn}{dT} L + \frac{dL}{dT} n \right)
\]

where \( L \) is the cavity length; \( dn/dT \) is the thermo-optic effect; \( dL/dT \) is the thermal expansion effect. If the medium in the F-P microcavity is composed of thermo-optic materials, the increase in temperature will change the refractive index of the material. Therefore, we use UV-curable films made of optical adhesive NOA73 (Norland Products Inc.) to fill the microcavities. This film has a high linear thermo-optic coefficient, up to \( 3.0 \times 10^{-4} \text{ K}^{-1} \). At the same time, NOA73 does not affect its excellent optical properties.

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Fig. 3 Relative wavelength shift of reflection peak and metal particle scattering peak of bare F-P cavity near 750 nm at different incident angles
after curing. The increase in temperature will change the refractive index of NOA73 and make the thermo-optic effect play a leading role. To verify the feasibility of modulating the light intensity with this thermo-optic material, we simulated the back-scattered intensity spectra at different temperatures under a large incident angle of $\theta = 70^\circ$ using a nanoparticle microcavity constructed with a 2 $\mu$m thick NOA73 film. The result is shown in Fig. 4. In the process of steadily increasing the temperature by 20 °C increment, each resonance wavelength has a different degree of blue shift. It is considered that although the drift amount of the resonance wavelength increases with the increase of the wavelength, the line width also becomes larger when the mode number is lower, which affects the temperature measurement result. To characterize the temperature tuning function of the microcavity structure, we define a relative temperature sensitivity parameter:

$$R_T = \frac{d\lambda/dT}{FWHM} = \frac{W_k}{FWHM}$$

(5)

where $W_k$ represents the amount of wavelength drift per unit temperature corresponding to the mode number $k$, and $FWHM$ represents the corresponding line width. The relative sensitivity parameter $R_T$ can characterize the sensitivity of the light intensity of the microcavity scattering spectrum when the ambient temperature changes. The greater $R_T$ is, the greater the change in scattered light intensity. By linearly fitting the temperature and the resonance wavelength, we calculated the relative temperature sensitivity parameter $R_T$ and the measurable temperature range $\Delta T$ at different resonance wavelengths, which is shown in Table 1. Besides, temperature sensitivity and microcavity thickness are positively correlated. Thicker microcavities can be used if higher temperature sensitivity is required. For traditional fiber optic temperature sensors, for example, multi-core fiber or laser-written Bragg fiber can work at a high temperature of 1000 °C, and measure the temperature change with a sensitivity of tens of pm/ C° in a wide working range. It means higher sensitivity and a wider working range are always mutually limited. The metallic nanoparticle microcavity coupling structure we proposed can flexibly realize different temperature detection requirements according to different F-P modes.

Fig. 4 Normalized scattering intensity spectra at different temperatures
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3 Experiments and results

A fundamental thermo-optical modulation unit for infrared detector using scattered visible light to read out infrared signals is proposed to be shown in Fig. 5a. The modulation unit for optical readout consists of three parts: a MIM structured infrared absorber layer in the photothermal conversion region, a fully dielectric F-P microcavity tuned to the incident visible light, and an array of metallic nanoparticles on the microcavity to scatter visible light. This unit can be supported by an infrared transparent substrate, or by a dielectric post or a suspended film for thermal isolation when thermal sensitivity is vital to consider. The metal nanoparticles are Al nanodisks with a diameter of 500 nm and a height of 100 nm with a period of 1 μm. The fully dielectric F-P cavity is composed of a top high-reflectivity layer of TiO₂ with thickness of 150 nm, a low-refractive index layer of NOA73 with thickness of 1.8 μm, and a bottom high-reflectivity layer of TiO₂ with 150 nm thickness. MIM structure is composed of 10 nm Ti layer, 685 nm SiO₂ layer and 100 nm Al layer. The absorption of infrared signals at different wavelengths can be achieved by changing the thickness of the intermediate dielectric SiO₂ layer. Samples for testing has been fabricated by magnetron sputtering of TiO₂ and Al, PECVD coating of SiO₂, spin-coating of NOA73 and electron beam lithography (EBL) of Al nanostructures. The surface morphology of the prepared Al nanoparticle arrays was observed by Quanta 200 environmental scanning electron microscope (ESEM), which is shown in Fig. 5b.

The diagram of dark field optical testing system is shown in Fig. 6. The core of the system is that the incident light exits through the fiber optic ring interface to the metal reflective wall of the dark field attachment, and the illumination light is processed into a ring by reflection. The ring illumination light can be directed to the sample surface at a large

| F-P mode | FWHM(nm) | \( W_e(nm\cdot K^{-1}) \) | \( R_f(\times 10^{-3} K^{-1}) \) | \( \Delta T(K) \) |
|----------|----------|---------------------|-----------------|--------------|
| 11       | 17.0     | 0.19                | 11.2            | —            |
| 10       | 23.1     | 0.20                | 8.7             | 150.8        |
| 9        | 23.3     | 0.27                | 11.8            | 163.8        |
| 8        | 26.3     | 0.30                | 11.4            | 207.7        |
| 7        | 36.2     | 0.31                | 8.6             | 259.4        |
| 6        | 60.3     | 0.37                | 6.1             | 306.8        |

Table 1 Resonance wavelength line width, temperature sensitivity, relative temperature sensitivity, and measurable temperature range in different F-P modes

Fig. 5 a Structural model of a thermal-optic modulation unit. b SEM images of Al nanoparticle arrays
angle of incidence, so that the reflected light is directed away from the imaging system at a large angle, and some of the scattered light is collected for imaging, which can isolate the bright background illumination light and greatly improve the contrast ratio by increasing the signal-to-noise ratio. This also makes the dark-field imaging approach suitable for optical real-time detection of LSPR anisotropy of metal nanoparticles at the micro- and nanoscale (Dijk et al. 2005).

Most of the illumination light irradiates on the surface of the F-P bare cavity without scattering with the sample and is later reflected to the far field; a small portion of the illumination light irradiates on the Al particle array and is scattered via the nanoparticle micro-cavity coupling structure with a change in direction, where some of the scattered light can be collected by the numerical aperture NA = 0.13 objective. The microscope barrel has two standard C interfaces to connect the Ocean Optics HR4000 spectrometer and the FL36RZSP type CCD camera for simultaneous imaging and spectroscopic measurements. The HR4000 spectrometer uses a Toshiba 3648 pixel line array CCD with an optical resolution of 0.02 nm (FWHM) and a spectral range of 200–1100 nm, and is connected by SMA 90 single-mode optical fiber (NA = 0.22). The output frame rate is 60 FPS.

As shown in Fig. 7, the scattering spectrum was obtained by using the spectrometer at an incidence angle of 60°. It can be found that the intensity of the scattering peak in the short-wave region differs from the numerical simulation results to some extent, and the position of the scattering peak is shifted to the left side of the simulation curve, and also the measured scattering peaks gradually overlaps with the other scattering peaks as the wavelength increases. The main reason for the difference between the test results and the simulation results is that the parameters such as thickness and refractive index of the experimentally prepared optical film and metal array have errors with the set simulation parameters, and the change of the thickness and refractive index of the F-P microcavity will directly affect the scattering intensity and peak position of the nanoparticles. Also, from the extended F-P cavity structure model (Ameling et al. 2010), the metal particles above the microcavity and the metal reflection layer below play a role similar to a plane mirror, introducing additional phase shift parameters $\phi_M$ and cavity elongation parameter $\Delta d$. The refractive index and thickness of the actual deposited Al nanodisks are somewhat

![Schematic of dark field optical system.](image)

Fig. 6 a Schematic of dark field optical system. b Measurement and simulation results of normalized scattering efficiency versus wavelength
different from the simulated values, which causes the phase shift parameter $\varphi_M$ and the cavity elongation parameter $\Delta d$ are also changed by a small amount.

In addition, the temperature-sensitive characteristics of the thermo-optic modulation unit were investigated by heating the substrate using a black body thermoregulator, and the scattering peaks in the spectral range from 600 to 640 nm were selected for characterization. As shown in Fig. 7a, it can be found that with the increase of temperature, the thermo-optic modulation unit is affected by the thermo-optic effect resulting in different degrees of red-shift of the resonance wavelength. The temperature sensitivity $W_{k,\text{test}} = 0.24 \text{nm} \cdot \text{K}^{-1}$ was calculated by taking the scattering spectrum data of both 20°C and 50°C. Simulation results were also calculated for the scattering spectrum when the temperature was varied, and $W_{k,\text{simu}} = 0.37 \text{nm} \cdot \text{K}^{-1}$ was obtained. There are two main reasons for the difference in temperature sensitivity between the test and simulation results, one is that the actual thickness of NOA73 after homogenization by the homogenizer deviates from the set parameters, and the other is that there will be some tiny bubbles in the process of homogenization, which leads to the actual optical thickness and refractive index of the thermo-optic layer decreasing. Meanwhile, in Fig. 7b, it can be found that the trend of relative light intensity change during the process of increasing from ambient temperature from 20°C to 50°C is increasing and then decreasing, and the change of relative light intensity at 614 nm is the largest, reaching 41.4%, and the change of light intensity per unit temperature is 1.38% K$^{-1}$.

4 Conclusion

Unlike the traditional electrical readout IR detectors, the optical readout IR detectors can effectively eliminate the constraint of thermal isolation by the readout circuit and are not limited by the noise bandwidth, which has a broad application prospect. In this paper, we propose an implementation scheme to read out IR signals using scattered visible light based on the thermo-optic effect of materials, and experimentally prepare and test the most critical thermo-optical modulation unit to prove the feasibility of the scheme in principle. Firstly, the scattering characteristics and temperature sensing performance of the nanoparticle microcavity coupled structure are analyzed by combining metallic nanoparticles with
F-P cavities, and compared with F-P cavities in the case of oblique incidence, and it is concluded that the nanoparticle microcavity coupled structure is less limited by the incidence angle and thus reduces demand of light source collimation. Then the scattering spectral characteristics and temperature-sensitive characteristics of the thermal-optic modulation unit were compared and analyzed together with the simulation results. It has a temperature sensitivity of 0.24 nm K\(^{-1}\) in the spectral range from 605 to 640 nm, and the maximum change in relative light intensity is 1.38% K\(^{-1}\) when the temperature changes at 614 nm.

For imaging application, an array configuration consisting of a large amount of thermal-optical unit are needed and arranged to independently modulate scattering spectra of each unit through local temperature variations induced by infrared radiation. The spatial scattering spectra can be readout through a multi-aperture microoptical system. Such microoptical systems have been applied for years to achieve ultrathin imaging or close-up imaging cameras (Hu et al. 2020). Moreover, if fast responses for some high-speed imaging applications are required, thinner structures with lower thermal mass can be adopted, by optimizing thin film layers or including advanced mico/nano structures (Ge et al. 2022) to unify the functions of infrared absorption and visible cavity resonance. It is expected that a compact and low cost infrared imaging sensor based on our scheme may be implemented in the future.

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**Declarations**

**Conflict of interest** The authors have not disclosed any conflict of interests.

**References**

Ameling, R., Langguth, L., Hentschel, M., Mesch, M., Braun, P.V., Giessen, H.: Cavity-enhanced localized plasmon resonance sensing. Appl. Phys. Lett. **97**, 253116 (2010). https://doi.org/10.1063/1.3530795

Dijk, M., Lippitz, M., Orrit, M.: Far-field optical microscopy of single metal nanoparticles. Acc. Chem. Res. **38**(7), 594–601 (2005). https://doi.org/10.1021/ch200539216

Enemuo, A.N., Chaudhuri, R.R., Song, Y., Sang-Woo, S.: Thermo-optic sensor based on resonance waveguide grating for infrared/thermal imaging. IEEE Sens J **15**(8), 4213–4217 (2015). https://doi.org/10.1109/jsen.2015.2414278

Exner, A.T., Pavlichenko, I., Lotsch, B.V., Scarpa, G., Lugli, P.: Low-cost thermo-optic imaging sensors: a detection principle based on tunable one-dimensional photonic crystals. ACS Appl. Mater. Interfaces **5**, 1575–1582 (2013). https://doi.org/10.1021/am301964y

Fu, J.Y., Shang, H.P., Shi, H.T., Li, Z.G., Ou, Y., Chen, D.P., Zhang, Q.C.: Optical sensitivity non-uniformity analysis and optimization of a tilt optical readout focal plane array. J. Micromech. Microeng. **26**(2), 025001 (2016). https://doi.org/10.1088/0960-1317/26/2/025001

Ge, H.N., et al.: Artificial micro- and nano-structure enhances long and very long-wavelength infrared detector. Acta Phys. Sin. (2022). https://doi.org/10.7498/aps.71.20220380

Georgouli, K., Jesus, M.D.R., Koidis, A.: Continuous statistical modelling for rapid detection of adulteration of extra virgin olive oil using mid infrared and Raman spectroscopic data. Food Chem. **217**, 735–742 (2017). https://doi.org/10.1016/j.foodchem.2016.09.011

Hong, B., Vallini, F., Fang, C.Y., Alasaad, A., Fainma, Y.: Simple nanoimprinted polymer nanostructures for uncooled thermal detection by direct surface plasmon imaging. ACS Appl. Mater. Interfaces **9**, 8327–8335 (2017). https://doi.org/10.1021/acsami.6b14054

Hu, T., et al.: CMOS-compatible a-Si metalenses on a 12-inch glass wafer for fingerprint imaging. Nanophotonics **9**(4), 823–830 (2020). https://doi.org/10.1515/nanoph-2019-0470
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