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A monolithic integrated medium wave Mercury Cadmium Telluride polarimetric focal plane array

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Abstract: A medium wave (MW) 640×512 (25 μm) Mercury Cadmium Telluride (HgCdTe) polarimetric focal plane array (FPA) was demonstrated. The micro-polarizer array (MPA) has been carefully designed in terms of line grating structure optimization and crosstalk suppression. A monolithic fabrication process with low damage was explored, which was verified to be compatible well with HgCdTe devices. After monolithic integration of MPA, NETD < 9. 5 mK was still maintained. Furthermore, to figure out the underlying mechanism that dominated the extinction ratio (*ER*), specialized MPA layouts were designed, and the crosstalk was experimentally validated as the major source that impacted *ER*. By expanding opaque regions at pixel edges to 4 μm, crosstalk rates from adjacent pixels could be effectively reduced to approximately 2%, and promising *ER*s ranging from 17. 32 to 27. 41 were implemented.

Key words: infrared physics, infrared polarimetric focal plane array, monolithic integration, Mercury Cadmium Telluride, extinction ratio

单片集成式中波碲镉汞偏振焦平面阵列

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摘要：本文提出了一种中波640×512(25 μm)的碲镉汞偏振焦平面阵列。从线栅结构优化和串扰抑制的层面，对微偏振片阵列进行了精心设计；探索了一种低损伤的片上制备工艺，经验证，该工艺与碲镉汞器件兼容良好。在完成微偏振片阵列的片上集成后，NETD仍能保持在9.5 mK以下。进一步地，为揭示主导消光比的潜在作用机制，设计了特殊的微偏振片阵列排布方式，从实验上证明了串扰效应是影响消光比的主要来源。将像元边缘的遮挡区域扩展至4 μm宽，能够将来自相邻像元的串扰率有效降低至大约2%，并实现在17.32~27.41之间的优良消光比。

关 键 词：红外物理；红外偏振焦平面阵列；单片集成；碲镉汞；消光比

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Introduction

Infrared (IR) focal plane arrays (FPA) with continually improved performance are widely used to detect the radiance intensities of target scenes[1-2]. Based on the two-dimensional spatial heat distributions, thermal imagers distinguish the target from the background through temperature differences. However, conventional radiance intensity imaging has limited recognition capabilities in complex scenarios with interferences like clouds, dust, and tree shadows, since the target-background contrast tends to be unclear[3-5].

For this issue, infrared polarization imaging has emerged as a viable solution. As a fundamental property of light, polarization reveals more intrinsic characteristics of the imaged object, such as surface features, shapes, and roughness[6-8]. Using the distinct polarization signatures between manmade and natural objects, the target-background contrast can be effectively en-

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hanced even under thermal equilibrium conditions. The target profiles can thus be highlighted and more details can be extracted[3, 9-10]. In order to acquire high-quality polarimetric images, it is urgent to develop high-performance polarimetric IRFPAs. Mercury Cadmium Telluride (HgCdTe) is considered to be an ideal material for its superior sensitivity and quantum efficiency[2].

Among various polarimeter configurations[11], thanks to the rapid development of micro-nano technologies, micro-polarizer array (MPA) based on division-of-focal-plane (DOFP) architecture has attracted extensive attention[12-14]. With less hardware redundancy and smaller occupation, MPA enables miniaturized, integrated, and compact polarimetric imaging systems. The MPA is usually discretely or monolithically integrated with the FPA. For discrete integration, although the MPA fabrication process is easier, additional bonding or gluing steps are required. Such steps increase the FPA-MPA separation, resulting in more significant diffractions. The crosstalk effects can thus be severer, which leads to reduced extinction ratios (ER)[15-16]. For instance, a discretely integrated medium wave (MW) 256×256 HgCdTe polarimetric FPA using gluing process exhibited moderate ERs around 5[17]. A long-wave (LW) 640×480 HgCdTe polarimetric FPA implemented by Indium bump bonding process possessed ERs less than 10[18]. For monolithic integration, with MPAs directly fabricated on the FPA surface, the diffractive crosstalks can be effectively suppressed, which enables higher performance upper limit. For example, with MPAs directly fabricated on chip, both MW and LW 256×256 HgCdTe polarimetric FPAs achieved ERs exceeding 10[19]. Nevertheless, it is still a bottleneck to meet the stringent process compatibility requirements posed by HgCdTe FPAs while attaining desirable performance.

In addition to integration technologies, the wave band should also be carefully selected. Compared with short wave (SW), MW and LW have significant advantages in night operation[5]. In this work, considering the manufacturing cost and technical difficulties of FPAs, the MW 640×512 (25 μm) HgCdTe FPA was chosen. The structural parameters of line gratings as well as the MPA layout have been designed to keep the balance between the performance and fabrication feasibility. An on-chip line grating fabrication process compatible with HgCdTe FPAs was exploited. Comprehensive tests on the performance of fabricated polarimetric FPAs have been conducted. In addition to performance tests, the crosstalk effect was also theoretically analyzed and experimentally characterized, which provided a better understanding about this mechanism that dominated ER.

1 Polarimetric FPA design

The schematic of the proposed monolithically integrated HgCdTe polarimetric FPA is shown in Fig. 1(a). The MPA consists of periodically distributed superpixels composed of 2×2 arranged micro-polarizers. Each pixelated micro-polarizer was formed by sub-wavelength metal line gratings. Within a superpixel, the polarization orientations of the micro-polarizers follow as a clockwise order of 0°, 45°, 90°, and 135°, respectively, as shown in Fig. 1(b). For an infrared radiation transmitting through the superpixel, its intensity is modulated by quad line gratings of different orientations, correspondingly generating four response signals: I_0, I_{45}, I_{90}, and I_{135}. With these four measured response signals, the Stokes parameters of the incoming radiation can be calculated via the following equations[20]:

$$S_0 = \frac{1}{2}\left(I_0 + I_{45} + I_{90} + I_{135}\right), S_1 = I_0 - I_{90}, S_2 = I_{45} - I_{135}. \quad (1)$$

The degree of linear polarization ($DOLP$) as well as the angle of polarization (AOP) can thus be calculated via the following equations:

$$DOLP = \frac{\sqrt{S_1^2 + S_2^2}}{S_0}, AOP = \frac{1}{2}\arctan\left(\frac{S_2}{S_1}\right) . \quad (2)$$

It should be noted that the relationship between the calculated and the actual $DOLP$ values takes the form as[21]:

$$DOLP = \frac{ER - 1}{ER + 1} DOLP_{act} , \quad (3)$$

where $DOLP_{act}$ denotes the actual $DOLP$. Clearly, the higher the ER, the more accurate the measured $DOLP$. For this purpose, a finite-different time-domain (FDTD) model was established to provide guidance on line grating optimizations. The boundary conditions as well as the meshing size have been properly set, as shown in Fig. 1(c).

The structural parameters of line gratings, i. e.,

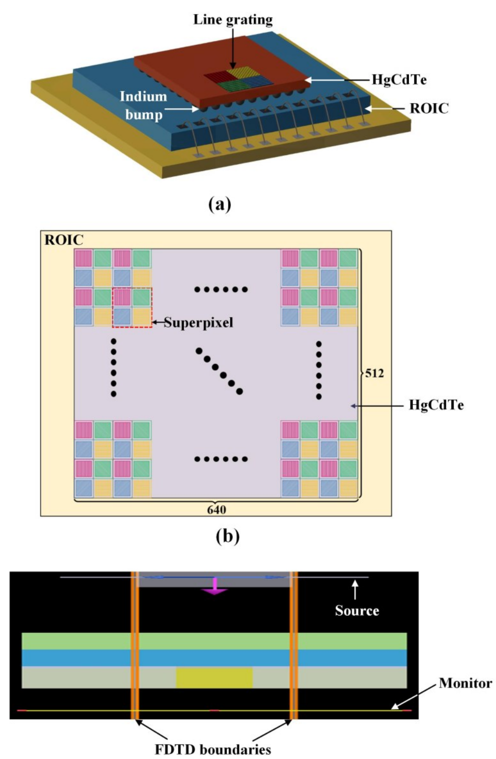

Fig. 1 Monolithic polarimetric FPA: (a) the schematic of a monolithic polarimetric FPA; (b) the arrangement of superpixels; (c) the established model to optimize structural parameters
图1 单片集成式焦平面阵列:(a)单片集成式焦平面阵列示意图;(b)超像元排布;(c)所建用于结构参数优化的模型

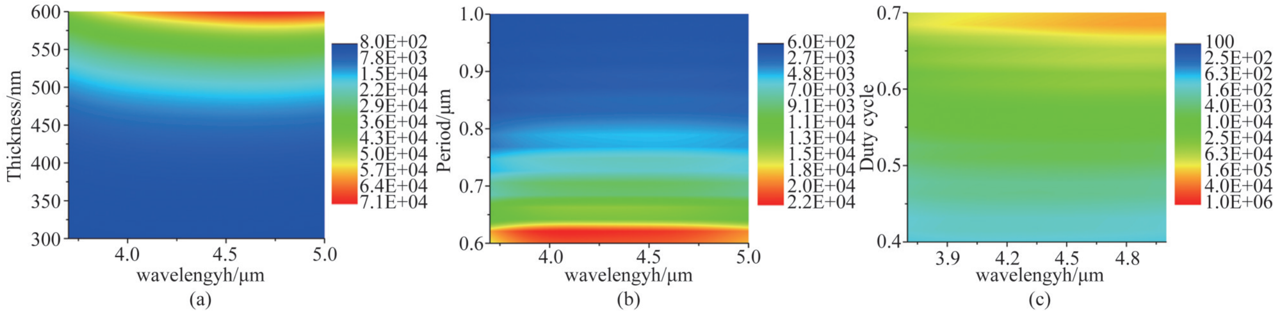

Fig. 2 *ER* variation tendencies with respect to different structural parameters: (a) thickness; (b) period; (c) duty cycle
图2 消光比随不同结构参数的变化趋势:(a)厚度;(b)周期;(c)占空比

thickness, period, and duty cycle, were initially set as 300 nm, 800 nm, and 50%, respectively. The variation tendencies of *ER* with respect to a certain parameter were simulated with the other two parameters maintained unchanged. As can be seen from Fig. 2(a), when the thickness increases, *ER* tends to be higher. However, too thick line gratings are not practical, since the re-deposition effect existing in the etching process can be detrimental to *ER* as well as the transverse magnetic (TM) wave transmittance. Figure 2(b) illustrates that *ER* increases with the reduced grating period, nevertheless, an excessively shrunk grating period will pose a challenge to the fabrication process. Regarding to Fig. 2(c), it can be inferred that *ER* rises rapidly with an improved grating duty cycle, however, simply improving the duty cycle can degrade the TM transmittance. To keep the balance between the process feasibility and polarization selectivity, the thickness ranging from 300 nm to 500 nm and period from 600 nm to 800 nm are suggested, while the duty cycle is kept as 50%.

It should be addressed that the above-mentioned model corresponds to an ideal case that the line gratings are infinitely distributed, wherein the crosstalk has not been involved. Nevertheless, for pixelated micro-polarizers, the distributed areas of line gratings are limited. Therefore, the crosstalks are nonnegligible, which results in significant *ER* reductions[16]. The crosstalk mechanisms can be categorized as two types: optical and electrical[21]. The optical crosstalk can be caused by the misalignment or diffraction. For the former one, if a micro-polarizer spans two pixels due to the MPA-FPA misalignment, the crosstalk occurs. The misalignment induced crosstalk can be effectively avoided by improving the alignment precision and setting opaque regions at the pixel edges. Regarding to the diffraction induced crosstalk, it appears when the radiation diffracts through the micro-polarizer aperture. The radiation propagates through the MPA-FPA separation, and ultimately impinges adjacent pixels[21]. Obviously, this kind of crosstalk tends to be more pronounced when the MPA-FPA separation increases[16]. In our previous work, with the entire superpixel modeled, the variation tendency of *ER* with respect to the MPA-FPA separation has been clarified[22]. With MPA directly fabricated on the FPA, the crosstalks caused by diffractions can be effectively suppressed.

The electrical crosstalk can be attributed to photo-generated carriers migrating from one pixel to the adjacent one. When the opaque regions at the pixel edges are expanded, the photo-generated carriers can be confined within the pixel central regions, thereby alleviating electrical crosstalks.

Although expanding opaque regions is effective for suppressing both optical and electrical crosstalks, this method could result in severe transmittance degradation. Therefore, a trade-off is necessary. Herein, two types of MPA layouts with different configurations of opaque regions are designed, as shown in Fig. 3. The first one, referred to as MPA layout A, follows as the design reported in our previous work, wherein the vertical and horizontal micro-polarizers have wider opaque regions than the diagonal ones[22]. When the opaque region widths are the same, due to the inconstant line grating lengths, the diagonally oriented pixels have inferior polarization selectivity. Therefore, the opaque region widths of differently oriented micro-polarizers were modified to balance *ER*s of differently oriented pixels. Another design is referred to as MPA layout B. Regardless of orientations, for all the polarizers, the widths of the opaque regions were set as 4 μm to suppress crosstalks. To compensate for the reduced photosensitive area, the period of line gratings was properly scaled down. This design aimed at verifying if enlarging opaque regions can implement *ER* enhancements at the expense of tolerable transmittance reduction. The structural parameters of these two MPA layouts are listed in Table 1.

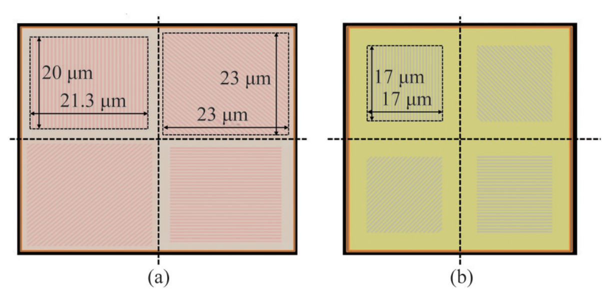

Fig. 3 MPA layout: (a) the previously reported MPA layout; (b) the modified one with expanded opaque regions
图3 微偏振片阵列版图:(a)前期报道的微偏振片阵列版图;(b)扩大遮挡区域的改进版

Table 1 Structural parameters of MPA layout A and B
表1 微偏振片阵列版图A和版图B的结构参数

	Thickness (nm)	Period (nm)	Duty cycle
MPA layout A	400	700	50%
MPA layout B	400	600	50%

2 Monolithic integration process

A simple and low-damage monolithic integration process was exploited to directly fabricate MPA on the surface of MW640×512(25 μm) HgCdTe FPA(Fig. 4(a)). The FPAs have been previously tested and the qualified ones were selected for the subsequent process.

Firstly, a 20 nm thick Ti layer and a 400 nm thick Au layer were successively deposited on the FPA by e-beam evaporation, serving as the structural layers (Fig. 4(b)). The Ti layer was employed to enhance the adhesion between the Au layer and the FPA. Subsequently, the MPA was patterned using the laser direct writing process (Fig. 4(c)) and etched using the ion-beam milling process (Fig. 4(d)).

During the deposition, the temperature of HgCdTe FPA should be strictly controlled below 80 °C. The e-beam evaporation, magnetic sputtering, and ion beam sputtering processes can all meet this requirement. All the Ti/Au layers attained by these three types of processes remain intact during the entire process flow. Given that keeping the continuities of the patterned line gratings is extremely important for attaining expected *ER*s, the qualities of metal layers were evaluated from the perspective of roughness. As can be clearly seen from Fig. 5, the e-beam evaporation allows for Au layers with the minimal roughness, which is selected as a preferable deposition technique in this work.

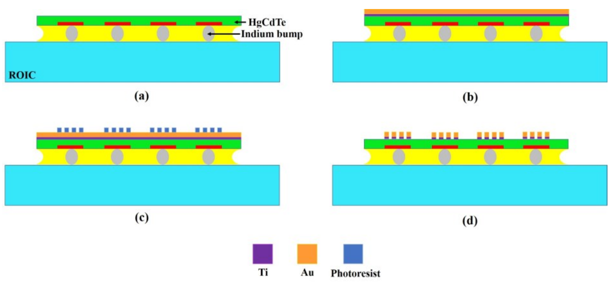

Fig. 4 MW 640 × 512 (25 μm) HgCdTe FPA: (a) monolithic integration process; (b) Ti/Au depositions; (c) laser direct writing; (d) iron-beam milling
图4 基于中波640 × 512(25 μm)焦平面探测器阵列:(a)片上工艺;(b)Ti/Au沉积;(c)激光直写;(d)离子铣刻蚀

For sub-wavelength line gratings, the lithography process is a crucial step which determines if the performance of the fabricated MPA addresses expectations. Herein the maskless laser direct writing technique was employed to achieve both flexible MPA layout modifications and line width down to 300 nm. The laser intensity and the focal length are two critical parameters. To determine the optimal process condition, a two-dimensional test matrix was employed in this work. Within the matrix, each "element" had the same pattern involving a group of line grating arrays with various duty cycles and line widths, whereas each row and column corresponded to a different laser intensity and focal length, respectively. Therefore, various combinations of exposure parameters together with their corresponding exposure effects were obtained. Consequently, the optimal parameters were determined, and the corresponding MPA pattern is given in Fig. 6. Another key indicator of lithography is referred to as misalignment. By properly designing the alignment mark and carefully calibrating the equipment, the misalignment down to ±1 μm has been realized, which can be totally covered by the opaque regions at the pixel edges. Therefore, the crosstalk led by misalignment can be effectively suppressed.

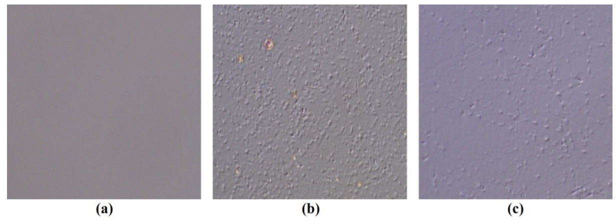

Fig. 5 Surface morphologies of Au layers fabricated by: (a) e-beam evaporation; (b) magnetic sputtering; (c) ion beam sputtering
图5 不同工艺制备的Au层表面形貌:(a)电子束蒸发;(b)磁控溅射;(c)离子束溅射

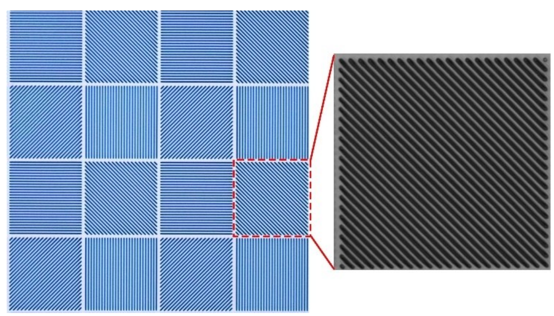

Fig. 6 Patterned line gratings with optimal process parameters of laser direct writing
图6 采用最佳激光直写工艺参数所得线栅图案

As for etching, ion milling featuring ion bombardment is a physical dry etching process, making it appropriate for etching multi-layer metals[23]. It should be noted that the particles of target materials are sputtered at different angles under ion bombardment[23]. The sputtered particles with large angles relative to the normal direction tend to redeposit onto the sidewalls of the readily etched patterns. This redeposition is deleterious to the etching profile, especially for subwavelength structures[24]. As can be seen from the cross-sectional profile shown in Fig. 7(a), with process conditions generally used for micrometer-scale patterns, i. e., normal incident of ion beam, low acceleration voltage, and high ion density, strong redeposition effect occurred and the line grating gaps were nearly filled up. To solve this issue, modifications such as increasing the incident angle of ion beam, raising the acceleration voltage, and reducing the ion density have been carried out, which greatly alleviated the redeposition effect, as shown in Fig. 7(b).

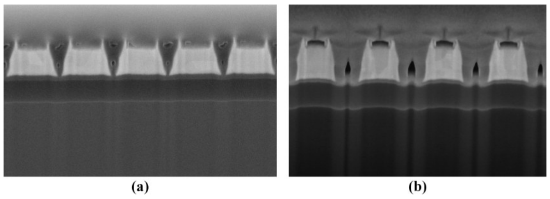

Fig. 7 Cross-sectional profiles of etched line gratings before (a) and after (b) process condition modifications
图7 线栅的横截面形貌:(a)工艺条件调整前;(b)工艺条件调整后

To sum up, through a series of process flow optimizations, the MPA was successfully fabricated on the FPA surface, and the damage was controlled. Figure 8 gives the scanning electron microscope (SEM) photographs of the fabricated MPA.

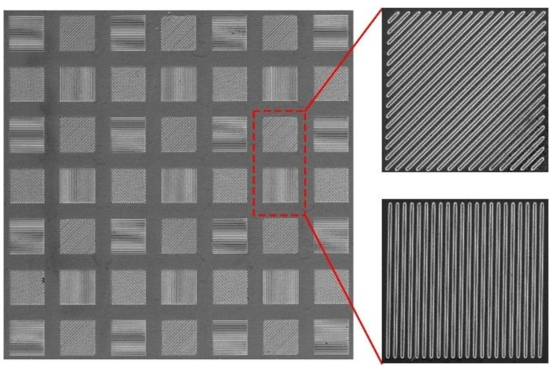

Fig. 8 SEM photographs of the monolithically fabricated MPA
图8 片上制备的微偏振片阵列SEM照片

3 Results and discussions

3.1 Test setup establishment

The performance of polarimetric FPA assemblies

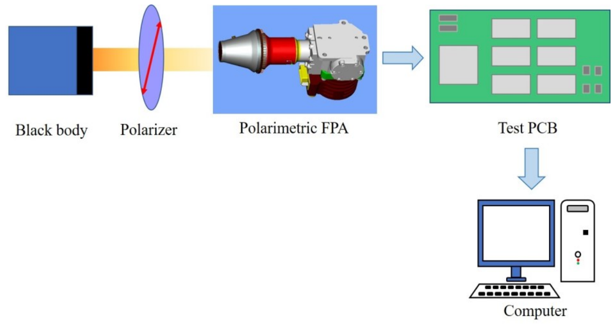

Fig. 9 Test setup of the polarimetric FPA
图9 偏振焦平面探测器阵列的测试平台

was characterized using the test setup as shown in Fig. 9. The black body served as a source of signal irradiation. The rotational polarizer with *ER* over 500 was utilized to modulate the unpolarized irradiation as the polarized one with various polarization angles. A customized test printed circuit board (PCB) was connected to the electrical interface of the assembly. The measured data could thus be transferred to the computer so that the performance indicators could be extracted.

3.2 Radiometric performance characterization

The fabricated polarimetric FPAs with MPA layout A and B were encapsulated in standard test Dewars. The radiometric performance of polarimetric FPAs was firstly measured. In this case, the polarizer was not needed. For both two types of polarimetric FPAs, pursuant to GB/T 17444-2013[25], the tests were performed at the liquid nitrogen temperature under the half-well integration capability filling condition, wherein the background and target temperatures were set as 293 K and 308 K, respectively. For both two types of polarimetric FPAs, the measured data before and after monolithic integration were summarized in Table 2.

In ideal conditions, after MPA fabrication, the integration time should be twice as long as that before, since half of the unpolarized radiance intensities are reflected by the line gratings. However, due to limited line grating distribution areas together with the fabrication tolerances, there are acceptable divergences between the measured integration time and the ideal one. In addition, after the MPA fabrication, the integration time of B-type polarimetric FPA only slightly extended com-

Table 2 Radiometric performance of two types of polarimetric FPAs before and after MPA fabrication (fab.)
表2 微偏振片阵列制备前后,两类偏振焦平面探测器阵列的辐射性能

	Polarimetric FPA type A		Polarimetric FPA type B	
	Before MPA fab.	After MPA fab.	Before MPA fab.	After MPA fab.
Integration time (ms)	3. 1	5. 2	3. 2	5. 9
Response signal (mV)	814	964	826	777
Peak detectivity ($cm\cdot Hz^{1/2}/W$)	1.64×10^{11}	1.51×10^{11}	1.84×10^{11}	1.24×10^{11}
Noise (mV)	0. 534	0. 535	0. 480	0. 490
NETD (mK)	9. 86	8. 39	8. 72	9. 49
Nonuniformity (%)	5. 32	11. 31	4. 53	8. 88
Effective pixel rate (%)	99. 981	95. 875	99. 758	96. 191

pared to that of the A-type one, indicating that the energy loss caused by the expanded opaque regions was not severe.

After the MPA fabrication, the response signal and noise did not worsen, indicating that the FPA damage induced by the process was controllable. According to GB/T 17444-2013, the peak detectivity can be determined via[25]:

$$D_p^* = G\frac{1}{M\cdot N-(d+h)}\sum_{i=1}^{M}\sum_{j=1}^{N}\sqrt{\frac{A_D}{2\tau}}\frac{R(i,j)}{V_N(i,j)}, \quad (4)$$

where G is the spectral factor, M and N are referred to as the FPA rows and columns, d and h are referred to as the dead and overheat pixels, and the sum of d and h represents the total blind pixels of the FPA. A_D and τ denote the pixel area and the half-well integration time. $V_N(i, j)$ represents the noise of a certain pixel, and $R(i, j)$ referred to as the responsivity can be calculated using the following formulas[25]:

$$R(i,j)=\frac{V_S(i,j)}{P}, \quad (5)$$

$$P=\frac{\sigma(T_2^4-T_1^4)A_D}{4F^{\#2}+1}, \quad (6)$$

where $V_S(i, j)$ denotes the response signal of a certain pixel, σ is referred to as the Stepan's constant, T_2 and T_1 are the target and background temperatures, respectively. According to Eqs. (4-6), after the MPA fabrication, the peak detectivity is supposed to reduce due to the increased integration time. The measured results were in accordance with the theoretical analysis.

Regarding to NETD, it takes the form as[25]:

$$NETD=\frac{1}{M\cdot N-(d+h)}\sum_{i=1}^{M}\sum_{j=1}^{N}\frac{T_2-T_1}{V_S(i,j)/V_N(i,j)}. \quad (7)$$

Similarly, the NETD variation tendencies can be inferred according to the response signals and noises before and after the MPA fabrication. For both two types of polarimetric FPAs, the measured results matched with the expectations.

What's more, the increased response nonuniformities for both two types of polarimetric FPAs can be mainly attributed to the ion beam etching. To improve the uniformity, the key point is to have a nearly maintained etching rate in both central and peripheral regions of the FPA. As for the effective pixel rate, upon blind pixel distribution diagrams as given in Fig. 10, for both two types of polarimetric FPAs, most blind pixels were concentrated on the FPA edges. Such a phenomenon is caused by the thick photoresist accumulated there. Faced with this issue, we have made some preliminary attempts, including modifying the spin-coating parameters of the photoresist and increasing the exposure energy at the FPA edges. With blind pixels remarkably reduced, the effective pixel rate has raised up to 98.23%, as shown in Fig. 11. To have more substantial progress, further research is ongoing.

Above all, despite expanded opaque regions, by taking appropriate compensation strategies such as reducing the line grating period, the B-type polarimetric FPA exhibited comparable radiometric performance as the A-type one.

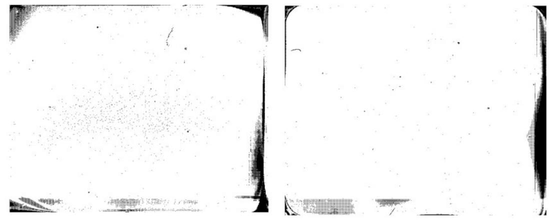

Fig. 10 Blind pixel distribution diagrams of (a) A-type and (b) B-type polarimetric FPAs
图10 偏振焦平面阵列的盲元分布图:(a)A型;(b)B型

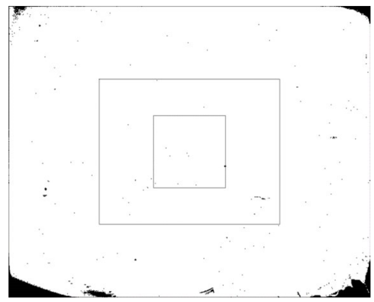

Fig. 11 Blind pixel distribution diagram of the polarimetric FPA after the preliminary process optimization
图11 初步优化工艺后,偏振焦平面阵列的盲元分布图

3.3 Extinction ratio extraction

With the polarizer incorporated into the test setup, the response signals under different polarizer rotation angles can be attained. The strongest and weakest signals, generated by TM and transverse electric (TE) incidents, are referred to as V_{TM} and V_{TE}, respectively. The ER can thus be determined via the following equation:

$$ER=\frac{V_{TM}}{V_{TE}}. \quad (8)$$

For both two types of polarimetric FPAs, the polarization response curves of differently oriented pixels are plotted in Figs. 12 and 13, respectively. The extracted ERs were listed in Table 3. Sinusoidal fittings have been carried out, which inferred that the measured data matched well with Malus' Law. It is evident that the B-type polarimetric FPA possessed significantly higher ERs than those of the A-type one. It is worth mentioning that for the B-type polarimetric FPA, the ER of 0°-oriented pixels was 7.26, which was lower than those of pixels with other orientations. It was found that the cycle duty of 0°-oriented line gratings was slightly reduced, which could result from the nonuniformities induced by the laser direct writing process.

In regard to the B-type polarimetric FPA, we have further optimized the entire MPA fabrication process and have formally encapsulated it in the standard metal micro-Dewar. As shown in Fig. 14, the measured ERs ranged from 17.32 to 27.41, which were greatly enhanced compared to those measured in the test Dewar. This phenomenon was caused by different transmittance ranges between the test and formal Dewars. For the test Dewar,

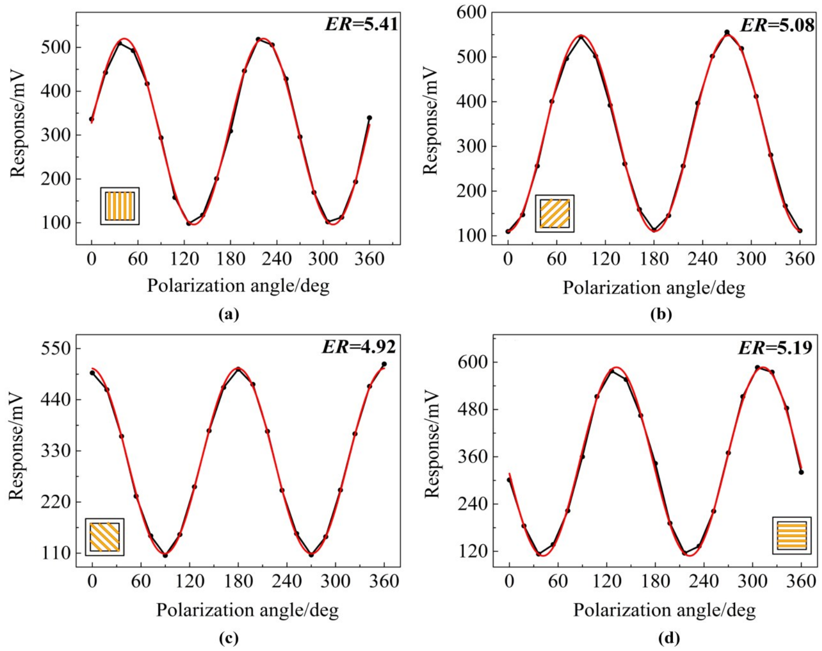

Fig. 12 Polarization response curves of pixels with (a-d) 0°, 45°, 90°, and 135°orientations for the A-type polarimetric FPA
图12 A型偏振焦平面阵列,(a-d)0°、45°、90°和135°取向像元的偏振响应曲线

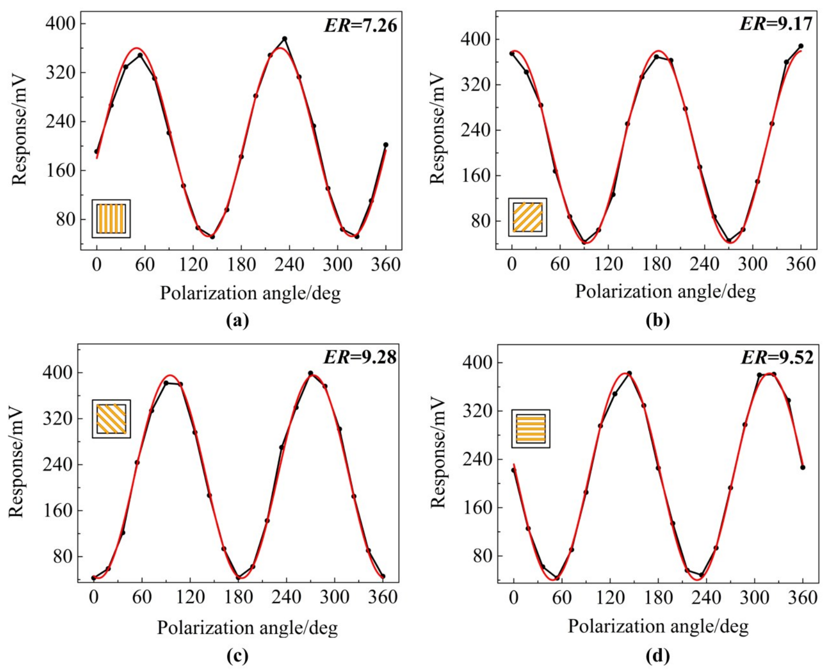

Fig. 13 Polarization response curves of pixels with (a-d) 0°, 45°, 90°, and 135°orientations for the B-type polarimetric FPA
图13 B型偏振焦平面阵列,(a-d) 0°、45°、90°和135°取向像元的偏振响应曲线

Table 3 *ER*s of two types of polarimetric FPAs
表3 两类偏振焦平面阵列的消光比

	ER			
	0°	45°	90°	135°
A-type polarimetric FPA	5. 41	5. 08	4. 92	5. 19
B-type polarimetric FPA	7. 26	9. 17	9. 28	9. 52

due to the absence of optical filter, the transmittance range was 1-5 μm. For incident lights with shorter wavelengths, the line gratings should be shrunk to the corresponding subwavelength scale to ensure sufficient polarization selectivity. However, regarding described MPA designed for 3. 7 - 4. 8 μm, the line grating period was too large for shorter wavelengths, thus leading to the reduced overall polarization selectivity over such a wide transmittance range. By contrast, for the formal Dewar, the optical filter was involved, and the transmittance range of 3. 7 - 4. 8 μm matched well with the designed

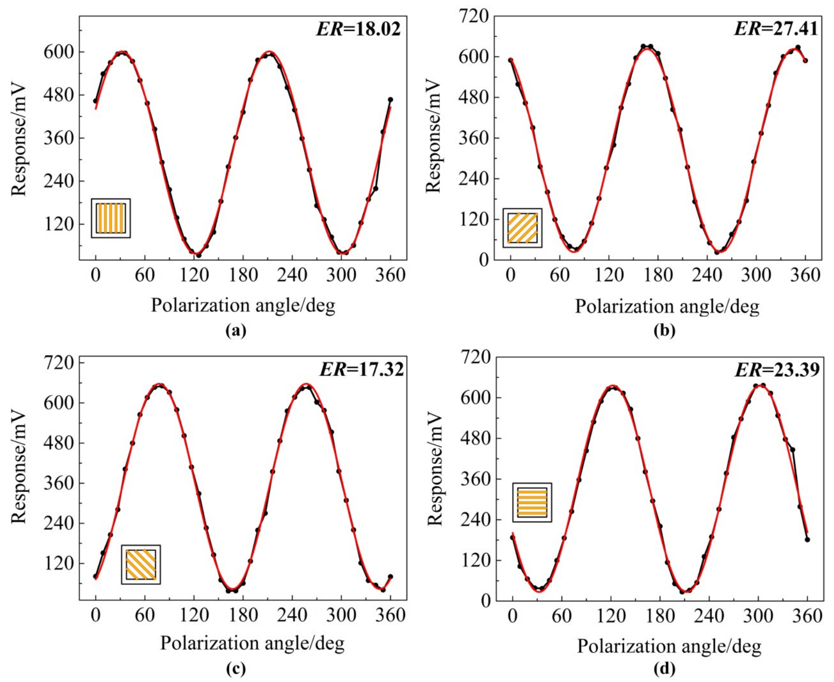

Fig. 14 Polarization response curves of pixels with (a-d) 0°, 45°, 90°, and 135° orientations for the formally encapsulated B-type polarimetric FPA
图14 正式封装后,B型偏振焦平面阵列(a-d)0°、45°、90°和135°取向像元的偏振响应曲线

MPA, thus achieving much higher *ER*s. Table 4 compares the described polarimetric FPA with the reported ones. The performance of this work is superior.

Above all, it has been experimentally validated that expanding opaque regions at the pixel edges is an effective methodology to improve *ER*s while maintaining promising radiometric performance. The *ER* differences of pixels with various orientations indicate that the uniformity of the whole monolithic integration process needs to be further improved, which will be a key focus in the future work.

3.4 Crosstalk rate determination

It is critical to have an insight into the dominant mechanism that limits *ER* so that further optimizations can be conducted to make greater performance breakthroughs. To figure out whether it is the crosstalk that leads to significant *ER* differences between two types of polarimetric FPAs, specialized MPA layouts have been designed to quantitatively characterize the crosstalk rates from adjacent pixels.

For instance, as shown in Fig. 15(a), the 0°-oriented pixels were all covered by Au layer. For these pixels, the signals generated by external radiations have been eliminated, and the measured ones are mostly contributed by the crosstalks from adjacent pixels. For pixels with other orientations, the crosstalk signals from their adjacent pixels can also be extracted using the similar layout designs.

The signal response of the pixel oriented in a certain polarization angle can be expressed as[27]:

$$\begin{aligned}
V_0 &= \frac{1}{2}(1-P)(q_1+r_1)V_{p1} \\
&\quad +P\left(q_1\sin^2(0-\alpha)+r_1\cos^2(0-\alpha)\right)V_{p1} \\
V_{45} &= \frac{1}{2}(1-P)(q_2+r_2)V_{p2} \\
&\quad +P\left(q_2\sin^2\left(\frac{\pi}{4}-\alpha\right)+r_2\cos^2\left(\frac{\pi}{4}-\alpha\right)\right)V_{p2} \\
V_{90} &= \frac{1}{2}(1-P)(q_3+r_3)V_{p3} \\
&\quad +P\left(q_3\sin^2\left(\frac{\pi}{2}-\alpha\right)+r_3\cos^2\left(\frac{\pi}{2}-\alpha\right)\right)V_{p3} \\
V_{135} &= \frac{1}{2}(1-P)(q_4+r_4)V_{p4} \\
&\quad +P\left(q_4\sin^2\left(\frac{3\pi}{4}-\alpha\right)+r_4\cos^2\left(\frac{3\pi}{4}-\alpha\right)\right)V_{p4}
\end{aligned} \quad , \tag{9}$$

Table 4 Performance comparison among this work and the reported ones
表4 已报道工作和本工作性能对比

	References			
	[19]	[26]	[17]	This work
Array size	256×256(30 μm)	1 024×1 024(25 μm)	256×256(30 μm)	640×512(25 μm)
NETD (mK)	Not given	Not given	Not given	9.49
ER	>10	Not given, expected to be over 10	~5	17.32~27.41

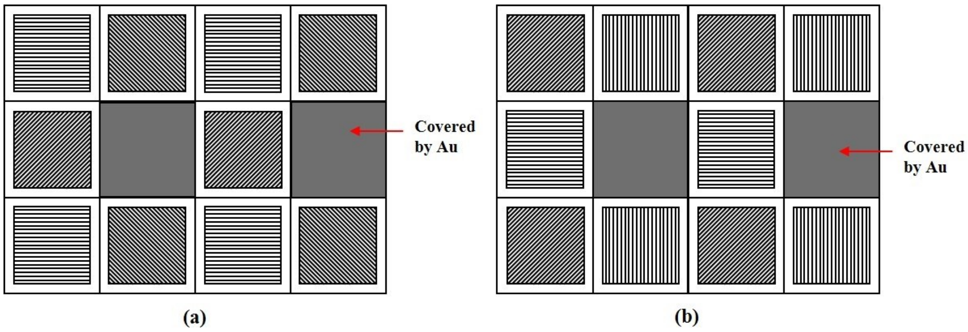

Fig. 15 Specialized MPA layout to determine crosstalk rates from adjacent pixels of (a) 0°- and (b) 45°- oriented pixels
图15 对于(a) 0°取向和(b) 45°像元,用于确定其相邻像元串扰率的专用版图

where P denotes the degree of polarization for the polarizer, V_{pi} (i=1, ⋯, 4) represents the response signal of the corresponding pixel before MPA fabrication, q_i and r_i (i=1, ⋯, 4) are referred to as TM and TE transmittances, respectively, α is the polarization angle of the incident light. In this equation, $\frac{1}{2}(1-P)(q_i+r_i)V_{pi}$ represents the response signal generated by the unpolarized portion of the incident lights transmitted through the polarizer, and $P\left(q_i\sin^2(\theta-\alpha)+r_i\cos^2(\theta-\alpha)\right)V_{pi}$, ($\theta = 0, \frac{\pi}{4}, \frac{\pi}{2}, \frac{3\pi}{4}$) represents the response signal generated by the polarized portion of the incident lights transmitted through the polarizer.

Taking the 0°-oriented pixels as an example, when these pixels were covered, the measured crosstalk signals from the adjacent pixels can be written as:

$$\begin{aligned}V_{c1} = {} & 2\left(\frac{1}{2}(1-P)(q_2+r_2)V_{p2}\right.\\ & \left.+P\left(q_2\sin^2\left(\frac{\pi}{4}-\alpha\right)+r_2\cos^2\left(\frac{\pi}{4}-\alpha\right)\right)V_{p2}\right)\chi\\ & +2\left(\frac{1}{2}(1-P)(q_4+r_4)V_{p4}+P\left(q_4\sin^2\left(\frac{3\pi}{4}-\alpha\right)\right.\right.\\ & \left.\left.+r_4\cos^2\left(\frac{3\pi}{4}-\alpha\right)\right)V_{p4}\right)\chi\end{aligned} \quad ,(10)$$

where χ denotes the crosstalk rate. In Eq. (10), the former and latter terms represent crosstalk signals contributed by the left and right 45°-oriented pixels, and upper and lower 135°-oriented pixels, respectively. The weak crosstalks from diagonal pixels were neglected. In ideal conditions, V_{p2} and V_{p4}, q_2 and q_4, r_2 and r_4 are equivalent, therefore, Eq. (10) can be simplified as:

$$V_{c1} = 2(q_2+r_2)V_{p2}\chi \quad . \quad (11)$$

In this case, the sum of crosstalk signals from adjacent pixels is a constant independent of the polarization angle.

However, the measured signals of the covered pixels appeared as sinusoidal curves, as shown in Fig. 16. The discrepancies can be ascribed to the response nonuniformities existed in the FPA as well as the polarization nonuniformities induced by the MPA. Such nonuniformities led to different V_{pi}, q_i, and r_i values. In this case, according to Eq. (10), the crosstalk signals sinusoidally varied with the polarization angle. The sum of the response signals from adjacent pixels is also plotted in Fig. 16(a). After fitting these two curves, it could be observed that their phases and periods were consistent. By calculating the ratio of these two groups of data, the crosstalk rate of 3.48% can be determined. Since both 0°- and 90°-oriented pixels are surrounded by two pairs of perpendicularly oriented pixels (45° and 135°), the depicted calculation process for 0°-oriented pixels is

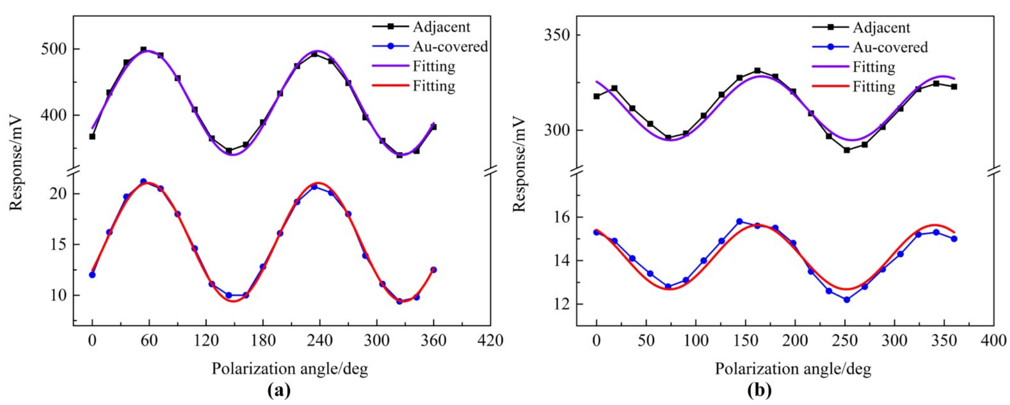

Fig. 16 Measured data used to determine the crosstalk rates from adjacent pixels of (a) 0°/90°- and (b) 45°/135°- oriented pixels for the A-type polarimetric FPA
图16 对于A型偏振焦平面阵列的(a) 0°/90°和(b) 45°/135°取向像元,用于确定其相邻像元串扰率的测试数据

equivalent for 90°-oriented ones. As for 45°/135°-oriented pixels, the MPA layout as shown in Fig. 15(b) is utilized, and the measured and fitted results are shown in Fig. 16(b), by which the crosstalk rate is determined as 4.54%.

For the B-type polarimetric FPA, the same methods were adopted. Based on the measured data and fitted curves as shown in Fig. 17, the crosstalk rates from adjacent pixels of 0°/90°- and 45°/135°-oriented pixels were calculated to be 1.70% and 2.06%, respectively.

For the A-type polarimetric FPA, when the imposed crosstalk signals were detracted, as shown in Fig. 18, the *ER*s of 0°- and 45°-oriented pixels recovered to 16.37 and 17.94, respectively. For the B-type polarimetric FPA, using the same method, the *ER*s of 0°- and 45°-oriented pixels recovered to 17.22 and 25.97, respectively. Obviously, for both two types of polarimetric FPAs, the re-extracted *ER*s became closer, strongly inferring that it was their distinct crosstalk rates that led to their significant *ER* differences. As previously discussed, the lithography misalignment of ±1 μm can be covered by the opaque regions. Besides, with MPA directly fabricated on the FPA surface, the diffraction induced crosstalks have been suppressed. Therefore, the optical crosstalks have been essentially minimized. It is reasonable to believe that the electrical crosstalk dominates *ER*. Furthermore, it should be noted that after re-extractions, for two types of polarimetric FPAs, there still are noticeable *ER* differences between their 45°-oriented pixels. This could be caused by process tolerances among different fabrication batches.

Above all, expanding opaque regions up to 4 μm can effectively suppress the crosstalk rate. Even so, simultaneously setting all the opaque region widths as 4 μm could still be a preliminary design. For pixels with various orientations, it would be a more flexible method to accordingly expand their opaque regions to different extents, which is expected to implement more balanced *ER*s.

4 Conclusions

In summary, this work developed a monolithic integrated MW HgCdTe polarimetric FPA with remarkable radiometric performance and polarization selectivity. A complete flow including design, fabrication, and test was comprehensively described, which would be beneficial for facilitating the practical applications of HgCdTe polarimetric FPAs.

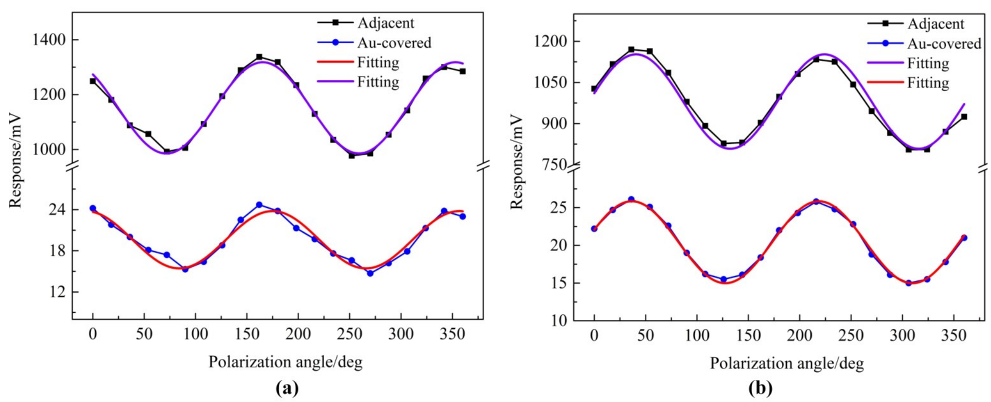

Fig. 17 Measured data used to determine the crosstalk rates from adjacent pixels of (a) 0°/90°- and (b) 45°/135°-oriented pixels for the B-type polarimetric FPA
图17 对于B型偏振焦平面阵列的(a) 0°/90°和(b) 45°/135°像元,用于确定其相邻像元串扰率的测试数据

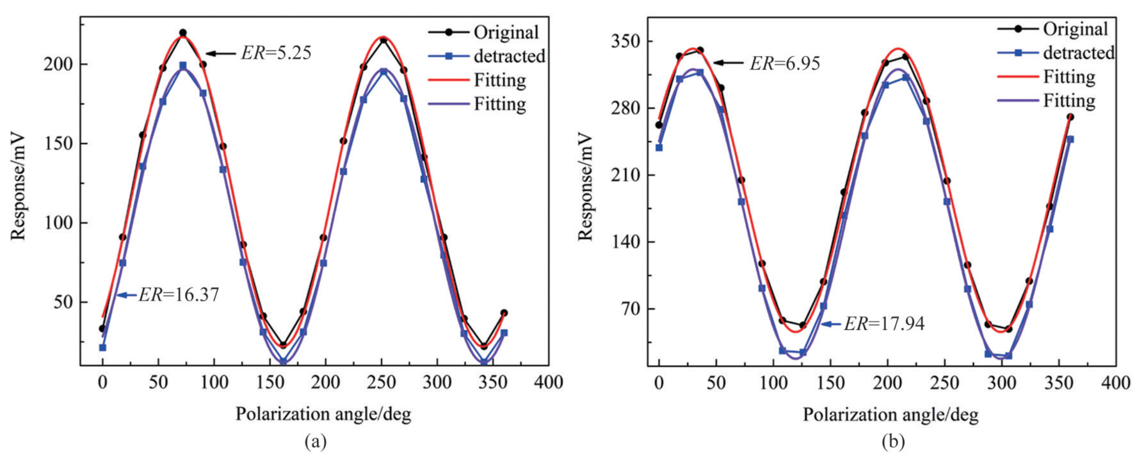

Fig. 18 Re-extracted *ER*s of (a) 0°- and (b) 45°-oriented pixels for the A-type polarimetric FPA
图18 A型偏振焦平面阵列中,(a) 0°和(b) 45°像元的重提取消光比

At design stage, systematical optimization for MPA layout has been carried out. Not only the structural parameters of line gratings, but also the crosstalks have been considered.

The feasibility and compatibility of proposed monolithic integration process have been testified, which achieved favorable *ERs* ranging from 17.32 to 27.41. More efforts in improving non-uniformity will be taken.

The crosstalk mechanism has been deeply discussed, which provided a helpful guidance on MPA designs. It was verified that properly expanding opaque regions implemented substantial *ER* enhancements at the cost of very limited radiometric performance scarification. With more flexible opaque region settings, the overall performance of the proposed polarimetric FPA is expected to be preferable.

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