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Irradiation effect of 2.79 μm mid-infrared laser on CMOS image sensor

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2.79 μm 中红外激光对 CMOS 图像传感器的辐照效应研究

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摘　要：研究中红外波段激光对 CMOS 图像传感器的辐照效应，对探索空间态势感知系统光学成像器件的激光干扰和损伤条件具有重要军事意义。开展了不同重频下 2.79 μm 中红外激光对 CMOS 图像传感器的干扰与损伤实验。观察到 CMOS 图像传感器的饱和、过饱和以及损伤产生的绿屏、彩色条纹、黑屏、亮线等一系列干扰损伤现象。同时测量了传感器各种辐照现象相对应的 2.79 μm 中红外激光干扰损伤阈值，研究了图像传感器辐照效应与激光重频之间的内在关系，分析了 2.79 μm 中红外激光对 CMOS 图像传感器的干扰损伤机理。研究表明，CMOS 图像传感器的激光损伤主要以材料的热熔融为主，热效应明显。在激光重频 10 Hz 的辐照下，饱和干扰阈值为 0.44 J/cm^2、过饱和阈值为 0.97 J/cm^2、损伤阈值为 203.71 J/cm^2。研究表明 CMOS 图像传感器具有很好的抗干扰和抗损伤能力，实验测得的相关阈值数据在空间激光攻防领域具有重要的参考价值。

关键词：中红外激光；　辐照效应；　CMOS 图像传感器；　损伤阈值
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0　引　言

自从 20 世纪 60 年代末期，美国贝尔实验室提出固态成像器件概念后，固体图像传感器便得到了迅速发展。互补金属氧化物半导体 CMOS(Complementary Metal-Oxide Semiconductor) 图像传感器与电荷耦合器件 CCD(Charge Coupled Device) 图像传感器的研究几乎同时起步。近年来，随着 CMOS 制造工艺水平的提高，它的画质日益趋近于 CCD，同时又具有价格便宜、体积小和集成度高等优点。因而被广泛应用于航空航天、安防监控工业控制、导航制导和图像识别系统等领域[1−7]。随着新型激光武器的发展，用于军事上的各类光电探测器几乎都面临着高功率激光武器的严重威胁。当探测器受到强激光辐照时，光敏元件会吸收激光能量使其温度升高，当温度达到一定值，便会发生损伤。目前，对可见光探测器的辐照效应研究主要集中在可见光、近红外波段 1.06 μm 等激光干扰毁伤 CCD 及 CMOS 图像传感器上[8−16]，这些都属于波段内研究，即用探测器工作波段内的激光对探测器进行辐照效应研究。而对于 CMOS 传感器工作波段外的中红外激光对其的干扰损伤研究，相关报道较少。随着越来越多的不同波段高能激光器的应用，这就造成了波段外激光对光学系统的损伤风险，有必要对这种波段外激光与光学元件的相互作用进行系统的实验研究。特别是在光电对抗中，当干扰和损伤用的是波段外激光时，是否还能对相关探测器产生有效的干扰和损伤，其作用机制如何，这具有重要的研究意义。2.79 μm 中红外激光处于大气窗口，拥有空气散射小、传播距离远等特点[17−20]，而且这一波段也是大多数天基侦察、监视、预警卫星等系统的工作波

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段，在未来空间应用上，高功率 2.79 μm 中红外激光有着广阔的应用前景。

因此，研究中红外波段激光对 CMOS 图像传感器的辐照效应，探索对天基空间态势感知系统光学成像器件的激光干扰和损伤条件，在激光攻防领域有着重要的应用参考价值。文中开展了 2.79 μm 中红外激光对 CMOS 图像传感器的干扰损伤实验，获取了相关阈值数据，主要讨论了激光干扰损伤机理，并分析比较了不同重频下的激光干扰损伤效果。

1 实验系统

整个辐照效应实验系统布局如图 1 所示。

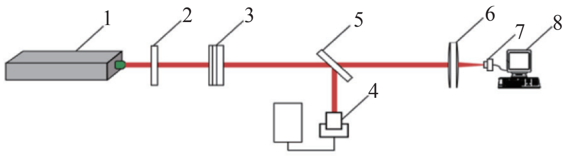

图 1 激光辐照效应实验系统示意图

Fig.1 Experimental system of laser irradiation effect

图中，1 为 2.79 μm 中红外激光器，2 为控制作用时间的定时器，3 为衰减片组，4 为激光能量计，5 为分束镜，6 为蓝宝石聚焦透镜，7 为 CMOS 图像传感器，8 为显示传感器图像的电脑。激光在 CMOS 图像传感器上的辐照时间由定时器控制。入射激光被分束镜分为两束：一束用于测量激光能量；另一束对 CMOS 图像传感器进行辐照。通过测定分光镜的分束比，就可以得到辐照在镜头前的激光能量的大小。

为研究激光辐照对 CMOS 图像传感器的干扰损伤效果，实验分为两个阶段：第一阶段，激光器的输出能量直接辐照到传感器上，即不放置图 1 中蓝宝石聚焦透镜，研究中红外激光对 CMOS 图像传感器的干扰效果；第二阶段，将蓝宝石聚焦透镜置于光路中，传感器位于透镜焦点处，研究中红外激光对 CMOS 图像传感器的损伤效果。采用 Nomarski 型的微分干涉相衬显微镜观察传感器样品的损伤形貌。

CMOS 图像传感器靶面像素阵列为 640 (水平)×480 (垂直)，靶面尺寸为 2.4 mm×1.8 mm，像素面积 3.75 μm × 3.75 μm，如图 2 所示。信号处理电脑连接 CMOS 相机，用来观察并记录激光辐照对相机成像的作用效果。

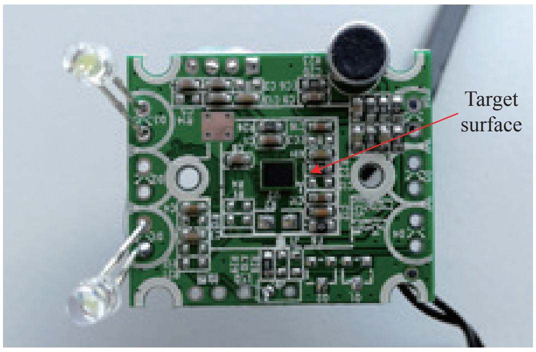

图 2 CMOS 图像传感器

Fig.2 CMOS image sensor

2.79 μm 中红外激光器增益介质为 Cr: Er: YSGG 晶体；泵浦源为脉冲氙灯，泵浦源发射的泵浦光由紧包型玻璃聚光腔会聚到增益介质棒，激光器输出脉宽 300 μs，其单脉冲能量输出范围为 10~820 mJ，重复频率 5 Hz 和 10 Hz。

2 实验结果与分析

2.1 干扰实验结果与分析

激光能量不经聚焦直接辐照到 CMOS 图像传感器上，传感器处光斑直径为 8 mm。在激光重频 5 Hz 辐照下，随着激光能量的提高，图像传感器出现了激光干扰：饱和现象和过饱和现象，两种激光干扰现象出现的时间随入射能量的变化情况如图 3 所示。当激光能量为 390 mJ 时，对应的激光能量密度为 0.76 J/cm^2，经过 122 s 的辐照，传感器出现全屏饱和现象，即全屏白色。当激光能量提高到 580 mJ 时，对应的能量密度为 1.15 J/cm^2，经过 30 s 的辐照出现饱和现象，42 s

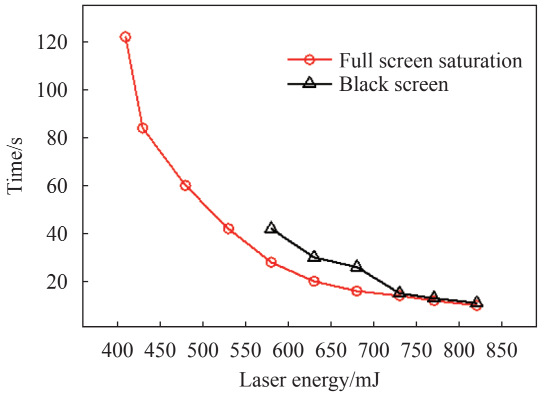

图 3 干扰现象随激光能量的变化情况 (重频 5 Hz)

Fig.3 Time of irradiation effect vs laser energy (Repetition frequency 5 Hz)

时出现过饱和现象，即全屏黑色现象，如图 4 所示。当激光能量为 820 mJ 时，经过 11 s 的辐照出现饱和现象，14 s 出现过饱和现象。在停止激光辐照一段时间后，图像传感器可以自动恢复至正常的工作状态。

图 4 传感器的过饱和黑屏画面

Fig.4 Phenomenon of oversaturation

在激光重频 10 Hz 辐照下，随着重频的升高，饱和现象和过饱和现象出现的时间如图 5 所示。当激光能量为 220 mJ 时，对应的能量密度为 0.44 J/cm^2，经过 108 s 的辐照传感器出现饱和现象全屏白色。当激光能量为 490 mJ 时，对应的能量密度为 0.97 J/cm^2，经过 11 s 的辐照出现饱和现象，16 s 出现过饱和现象全屏黑色。当激光能量为 0.72 J 时，对应能量密度为 1.43 J/cm^2，传感器经过 5 s 的辐照出现饱和现象，经过 7 s 的辐照出现过饱和现象。

全屏白色这种饱和现象的产生是由于像元受到激光辐照后，CMOS 的光电二极管产生大量的光生电荷，使得势阱被逐渐填满，CMOS 输出的电压信号饱和，从而出现视频画面逐渐变白，从而出现饱和现象，此时的激光能量密度即为饱和阈值。当入射激光强度高于饱和阈值、但未使得传感器发生不可逆的损坏时，传感器出现过饱和现象。CMOS 图像传感器集成了列级相关双采样 CDS(Correlated Double Sampling) 输出电路，当入射激光强度高于饱和阈值时，将影响 CDS 中参考信号 (res) 的采集，参考信号电压 $V_{\rm res}$ 升高，信号电压 $V_{\rm sig}$ 与参考电压 $V_{\rm res}$ 差值减小，输出视频信号受到干扰，从而导致强光辐照下器件出现过饱和现象，表现为从白色转变为全屏黑色，此时的激光能量密度为过饱和阈值。

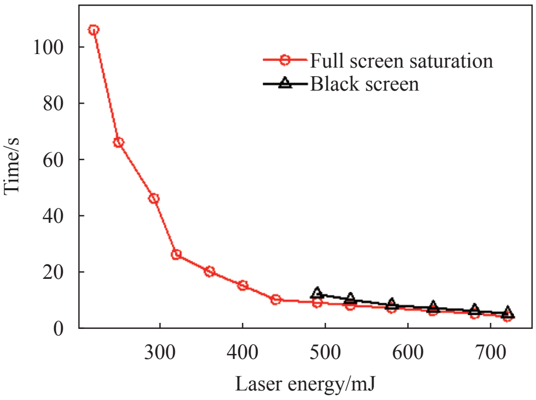

图 5 干扰现象随激光能量的变化情况 (重频 10 Hz)

Fig.5 Time of irradiation effect vs. laser energy (Repetition frequency 10 Hz)

另外，实验研究表明，重频提高后，由于更多激光脉冲涌入的累积效应，使得 CMOS 图像传感器达到全屏饱和或过饱和所需的激光能量更小，时间更短。

2.2 损伤实验结果与分析

实验光路放入中红外蓝宝石聚焦透镜，聚焦镜焦距 200 mm，双面镀 2.79 μm 波长增透膜，测得传感器处聚焦光斑直径为 0.5 mm。在激光重频 5 Hz 辐照下，当激光能量为 340 mJ 时，对应的能量密度为 173.16 J/cm^2，在辐照开始的 1 s 内接连出现了全屏白色、全屏黑色画面，经过 1 min 29 s 辐照后，视频画面出现了绿屏现象，如图 6 所示，画面停滞。辐照结束后，绿屏消失，视频画面恢复。说明此条件辐照下，传感器未出现损坏。当激光能量为 390 mJ 时，对应的能量密度为 198.63 J/cm^2，在辐照开始的 1 s 内直接出现全屏白色，10 s 后，出现绿屏，55 s 后，不再呈现视频画面。辐照结束后，视频显示为带有若干红色、绿

图 6 传感器的干扰画面

Fig.6 Phenomenon of green screen

色、蓝色条纹的黑色亮线画面，如图 7 所示，且不再对外界光信号产生响应。说明此条件辐照下，传感器已经损坏。两种入射激光能量下的辐照现象与作用时间的关系如图 8 所示。

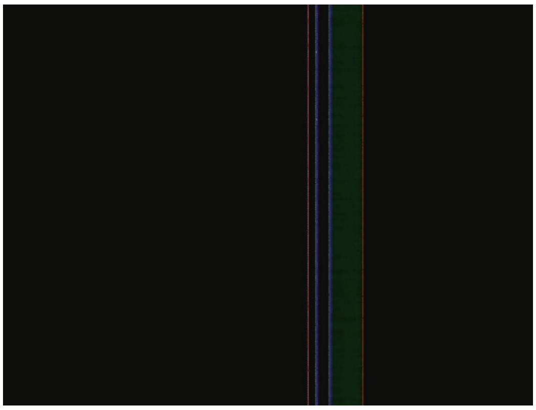

图 7 传感器的损伤画面

Fig.7 Damage phenomenon of CMOS

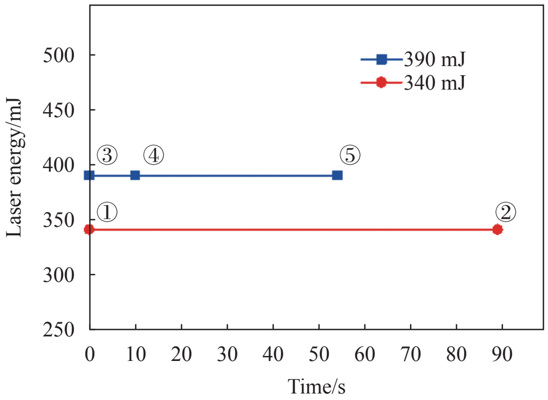

图 8 传感器激光能量与作用时间的关系 (重频 5 Hz) ①饱和/过饱和，②绿屏，③过饱和，④绿屏，⑤损坏

Fig.8 Time of irradiation effect vs. sensor laser energy (5 Hz)① saturated/ oversaturated, ② green screen, ③ oversaturated, ④ green screen, ⑤ damage

在激光重频 10 Hz 辐照下，随着重频的升高，当激光能量为 360 mJ 时，对应的能量密度为 183.35 J/cm^2，激光辐照 2 s 时出现全屏白色，3 s 时出现全屏黑色，12 s 时视频画面停滞。辐照结束后，视频画面恢复。说明此条件辐照下，传感器未出现损坏。当激光能量为 400 mJ 时，对应光斑能量密度为 203.71 J/cm^2，在辐照开始的 1 s 内直接出现全屏白色，2 s 后出现绿屏画面，9 s 后，不再呈现视频画面。辐照结束后，视频显示为带有若干红色、绿色、蓝色条纹的黑色亮线画面，和图 7 画面相同，且不再对外界光信号产生响应，说明探测器已经损坏。两种入射激光能量下，辐照现象与作用时间的关系如图 9 所示。

激光辐照后，CMOS 图像传感器在微分干涉显微镜下观察到的损伤形貌如图 10 所示。可以观察到，激光光斑辐照区域出现了明显的熔融损伤，辐照中心区域激光能量过高导致大片像元材料烧蚀蒸发，区域外围受热明显，但未出现裂纹。说明 2.79 μm 中红外激光对 CMOS 传感器的损伤主要以材料的热熔融为主，热效应明显，传感器表面的光敏阵面以及部分信号传输电路遭到高温破坏，使得信号的选通、输出发生障碍，探测能力下降并出现上述“绿屏”、“彩色条

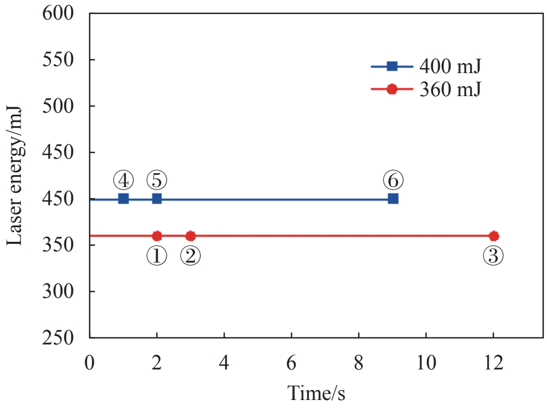

图 9 传感器激光能量与作用时间的关系 (重频 10 Hz) ①饱和，②过饱和，③画面停滞，④过饱和，⑤绿屏，⑥损坏

Fig.9 Time of irradiation effect vs. sensor laser energy (10 Hz) ① saturated, ② oversaturated, ③ stagnation of picture, ④ oversaturated, ⑤ green screen, ⑥ damage

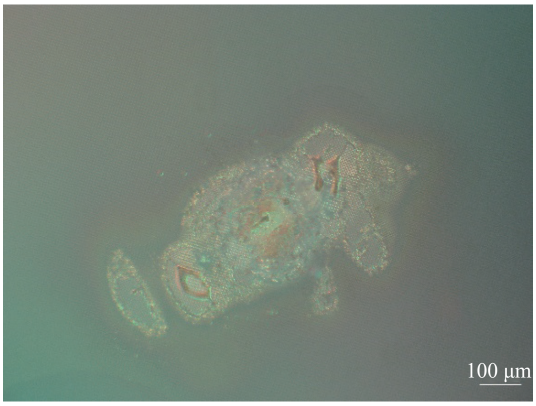

图 10 传感器的损伤形貌 (203.71 J/cm^2, 10 Hz)

Fig.10 Damage morphology of CMOS image sensor (203.71 J/cm^2, 10 Hz)

纹”画面。

3 结 论

开展了不同重频下 2.79 μm 中红外激光对 CMOS 图像传感器的辐照效应实验，观察到全屏饱和、过饱和黑屏以及损伤产生的绿屏、彩色条纹、黑屏亮线等一系列干扰损伤现象，讨论了激光干扰损伤机理。实验研究表明：激光重频对干扰效果影响很大，高重频下 CMOS 图像传感器达到全屏饱和或全屏黑屏所需的激光能量更小，时间更短。2.79 μm 中红外激光对 CMOS 传感器的损伤主要以材料的热熔融为主，热效应明显。

研究表明：在激光重频 10 Hz 的条件下，2.79 μm 中红外激光对 CMOS 图像传感器的干扰损伤阈值分别为：饱和干扰阈值为 0.44 J/cm^2、过饱和阈值为 0.97 J/cm^2、损伤阈值为 203.71 J/cm^2。可见，CMOS 图像传感器损伤阈值远高于干扰阈值，说明要想使 CMOS 损伤需要的激光能量必须很高，这一特征也符合 1.06 μm 近红外激光损伤 CMOS 图像传感器的实验特征。在航天设备中，CMOS 图像传感器具有很好的抗干扰和抗损伤能力，实验测得相关阈值数据在激光攻防领域具有重要的参考价值。

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Irradiation effect of 2.79 μm mid-infrared laser on CMOS image sensor

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Abstract:

Objective The CMOS image sensors are widely used in aerospace, security monitoring, industrial control, navigation and guidance, image recognition systems and other fields. Most of researches on laser irradiation effect of CMOS image sensor mainly focus on visible and near infrared bands. With the application of more and more lasers with different wavelengths, there is a great risk of damage to optical systems irradiated by out-of-band lasers, and it is necessary to conduct systematic experimental studies on the interaction between out-of-band lasers and photo detectors. In the photoelectric countermeasure, it is very important to study whether the interference and damage can be effectively caused to the detector when the interference and damage are irradiated by the out-of-band laser, and what its mechanism is. The wavelength of 2.79 μm mid-infrared laser is in the atmospheric window, which has the characteristics of small air scattering and long propagation distance. This band is also the working band of most reconnaissance satellites, surveillance satellites, early warning satellites and other space-based systems. In the future space applications, the high-power 2.79 μm mid-infrared laser has a broad application prospect. Therefore, it is of great reference value in the laser attack and defense field to study the irradiation effect of mid-infrared laser on CMOS image sensor.

Methods In the experiment, the CMOS image sensor irradiated by 2.79 μm mid-infrared laser is carried out (Fig.1). The computer is connected to the output signal of CMOS image sensor to observe and record the effect of laser irradiation. In order to study the damage effect of laser irradiation on CMOS image sensor, the experiment is divided into two stages. In the first stage, the laser energy is directly irradiated on the sensor without the sapphire focus lens, and the interference effect of 2.79 μm mid-infrared laser on CMOS image sensor is studied. In the second stage, the sapphire focus lens is placed in the optical path to study the damage effect of 2.79 μm mid-infrared laser on CMOS image sensor. The differential interference contrast (DIC) microscope is used to observe the damage morphology of CMOS sensor samples.

Results and Discussions The experimental results of laser interference show that saturation and oversaturation appears on the CMOS image sensor with the increase of laser energy (Fig.3). After stopping laser irradiation for a period of time, CMOS can automatically return to the normal working state. The experimental results show that with the increase of the repetition frequency, CMOS image sensor needs less laser energy and less time to achieve saturation or oversaturation of full screen (Fig.5). The experimental results of laser damage show that the phenomenon of saturation, oversaturation, black screen, green screen and bright line are observed with different laser repetition frequency (Fig.8-9). The damage morphology shows that obvious melting damage occurs in the irradiation area of laser spot, and the high laser energy in the center of beam leads to the ablation and evaporation of a large area of pixel material, and the periphery of the spot area is obviously heated, but no cracks appear (Fig.10). It shows that the damage of 2.79 μm mid-infrared laser on CMOS sensor is mainly due to the thermal melting of materials, and the thermal effect is obvious.

Conclusions The experimental results indicate that the CMOS image sensor has good anti-interference and anti-damage ability. The damage thresholds of CMOS image sensor irradiated by 2.79 μm mid-infrared laser at a 10 Hz pulse repetition frequency are 0.44 J/cm^2 for saturation, 0.97 J/cm^2 for oversaturation, and 203.71 J/cm^2 for damage, respectively. It can be seen that the damage threshold of the CMOS image sensor is much higher than its interference threshold. The experimental results show that the damage mechanism of CMOS image sensor is mainly melting damage, and the thermal effect is obvious.

Key words: mid-infrared laser; irradiation effect; CMOS image sensor; damage threshold

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