



Q-switched and gain-switched Fe:ZnSe lasers tunable over 3.60–5.15 μm

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Abstract: We report on room temperature gain-switched and Q-switched Fe:ZnSe lasers tunable over 3.60–5.15 μm pumped by radiation of an 2.94 μm Er:YAG laser. The maximum output energy was measured to be 5 mJ under 15 mJ of pump energy in gain-switched regime. We also demonstrated a mechanically Q-switched regime of oscillation of Fe:ZnSe lasers. This approach could be attractive for the development of high-energy short-pulse solid-state mid-IR systems operating over 3.6–5.2 μm spectral range.

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1. Introduction

The development of middle infrared (mid-IR) tunable solid-state lasers is of considerable interest for a variety of scientific, industrial, and medical applications. Iron-doped binary (e.g., ZnSe, ZnS, CdSe, CdS, ZnTe) and ternary (e.g., CdMnTe, CdZnTe, ZnSSe) chalcogenide crystals are very promising for tunable solid-state lasers operating over the 3–8 μm spectral range [1–3]. The most significant results have been reported for iron doped ZnSe crystals. The output power up to 9.6 W from a CW Fe:ZnSe laser was demonstrated in a non-selective cavity at 4.2 μm [4]. The lifetime of the upper laser level 5T_2 of the Fe^{2+} ion in a ZnSe matrix falls with temperature from $\tau = 55 \mu\text{s}$ at 77 K to 370 ns at room temperature (RT) due to the increase of non-radiative relaxation [5]. The RT Fe:ZnSe lasing in a gain-switched operation mode was proposed and demonstrated in [6,7]. The progress in RT Fe^{2+} lasers strongly depends on availability of high-energy nanosecond pump lasers operating near the maximum of the Fe^{2+} absorption band (2.7–3.2 μm). The output energy of the Fe:ZnSe laser at RT reached 1.4 J at ~150 ns pulse duration when pumped by the radiation of HF laser [8]. However, HF chemical lasers toxicity to humans limits a number of their possible applications.

One of the applications of Fe:ZnSe lasers is to optically pump ultra-short CO_2 lasers and amplifiers. A carbon dioxide gas laser possesses a unique (multi-Joule) energy storage capability for amplification of 10 μm pulses but does not have the bandwidth necessary to amplify ultra-short pulses. Its bandwidth can be increased through the collisional broadening of spectral lines at high pressures, but traditional discharge pumped CO_2 lasers are extremely difficult to build at pressures above 10 atm as the electric discharge becomes unstable. Optically pumped CO_2 lasers face no such pressure limitation, and offer a potentially efficient and compact alternative [9,10].

In our paper we report on development of RT 3.60–5.15 μm tunable mid-IR Fe:ZnSe laser pumped by a radiation of mechanically Q-switched Er:YAG laser. This nanosecond Fe:ZnSe laser is a first stage of future master oscillator - power amplifier (MOPA) system for optical excitation of CO_2 lasers and amplifiers of sub-ps pulses. In addition, we also report on Q-switched operation of Fe:ZnSe laser pumped by a radiation of free running Er:YAG.

2. Mechanically Q-switched Er:YAG pump laser

An Er:YAG laser operating at $2.94\ \mu\text{m}$ is a convenient pump source for a Fe:ZnSe laser. The $2.94\ \mu\text{m}$ oscillation wavelength nicely overlaps with the absorption band of Fe^{2+} ions in II-VI materials. The output energy of Er:YAG laser could exceed 25 J from a single oscillator in free running regime. The Fe:ZnSe laser with output energy up to 7.5 J @ $4.3\ \mu\text{m}$ pumped by Er:YAG laser was reported in [11].

The effective free running operation of a Fe:ZnSe laser requires cooling of the gain element to at least $\sim 220\ \text{K}$ due to temperature quenching of the upper laser level. On the other hand the effective RT operation of Fe:ZnSe laser requires pump pulses to be shorter than the upper laser level lifetime (380 ns [6,12]). While, there are numerous publications on Q-switching of $2.9\ \mu\text{m}$ Er:YAG laser cavities by all the known techniques (such as electro-optics [13], acousto-optics [14], saturable absorber [15]), a stable effective operation of Q-switched Er:YAG laser is still a challenge due to a low optical damage threshold and resource of work of the used mid-IR Q-switch materials. Therefore, several mechanical Q-switches which are not sensitive to the wavelength were proposed and developed. The Er:YSGG laser at $2.79\ \mu\text{m}$ with a Q-switch based on frustrated total internal reflection (FTIR) was reported in [16] and demonstrated several tenths of mJ in a single pulse. The major disadvantages of FTIR Q-switches are relatively large switching times, high required operation voltage, and difficult control of the beam quality. Recently, very compact devices with low consumption power, high repetition rate ($\sim 1\ \text{kHz}$), and high threshold for optical damage were reported in several publications [17,18]. For one of these experiments [18], a compact mirror scanner, based on a torsion bar spring, was used as the mechanical Q-switch of the laser cavity. The resonant oscillation of a compact mirror at 4.6 kHz was achieved by 5 V sinusoidal signal applied to wire coil with average electric drive power of 62 mW. However, due to a limited angular speed, the maximum output energy in flashlamp pumped Er:YAG laser was limited to $\sim 6\ \text{mJ}$. Further increase of the pump energy results in multi-pulse oscillation.

The mechanical Q-switch based on rotation prism or mirror have been studied for many decades [19]. Modern brushless DC motors feature good torque characteristic, adjustable speed range with maximum above 80000 rpm, and long life span. A Q-switched Er:YAG laser developed for medical applications with a pulse duration of $\sim 300\ \text{ns}$ was reported in [20].

In our experiments, we focused on development of mechanically Q-switched Er:YAG laser as a pump source for tunable RT Fe:ZnSe with a pulse duration shorter than 150 ns. The scheme of Q-switched Er:YAG laser is shown in Fig. 1.

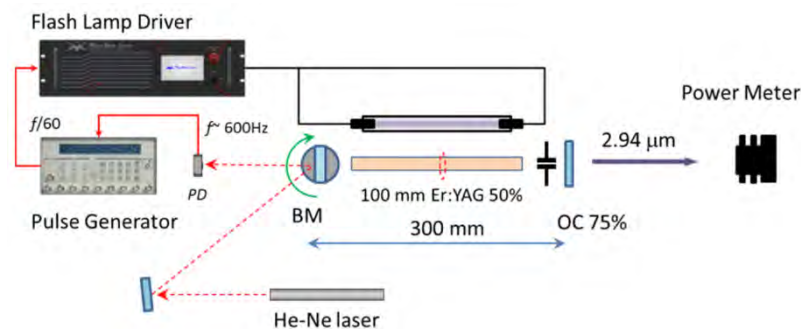


Fig. 1. Basic scheme of mechanically Q-switched Er:YAG laser.

In our experiments we use 100 mm long Er(50%):YAG crystal with 4 mm diameter. The rod had AR-coatings on both end surfaces. The laser cavity was formed by a flat back mirror and a flat output coupler with reflectivity 75%. The laser stability was provided by a thermal lens in the Er:YAG crystal. The mechanical Q-switching was demonstrated using rotation of a

flat back mirror. He-Ne laser radiation reflected from the rotating mirror was detected by Si photodiode and formed input pulses for a pulse generator. The repetition rate of the triggering pulse was decreased to 10 Hz by digital generator. The pulse generator also provides adjustable delay for triggering of flash lamp driver. We used KALD 20-10 (*MegaWatt Lasers*) flashlamp driver, capable to form up to 120 J pulses with 200 μ s pulse duration. The rotation rate of a back mirror was optimized to generate a single Er:YAG pulse with a maximum output energy.

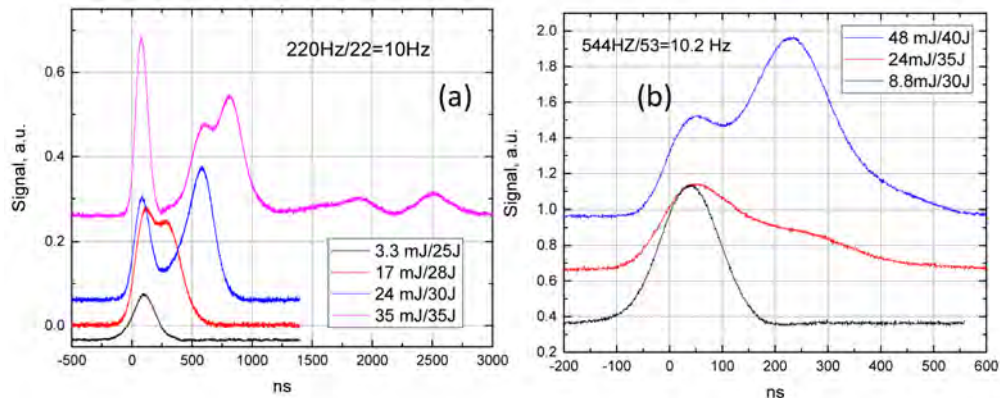


Fig. 2. Temporal profiles of the mechanically Q-switched Er:YAG laser for different pump energies and rotation rates of the back mirror.

Figure 2 shows the temporal profiles and output energies of the mechanically Q-switched Er:YAG laser with 220 Hz and 544 Hz rotation rates of the back mirror. As one can see from the Fig. 2, at low pump energy laser oscillation consists of a single pulse with 150-200 ns pulse duration. An increase of the rotational speed results in increase of the laser threshold; however, it allows a higher energy in a single pulse. It is noteworthy that the time interval between spikes was decreased from \sim 500 to \sim 200 ns when rotation rate was increased from 220 Hz to 544 Hz. It results in overlapping of the first and second spikes with formation of a single pulse with \sim 400 ns pulse duration. The maximum output energy in single 300 ns pulses was measured to be up to 55 mJ at 2.94 μ m in multi-mode regime of operation.

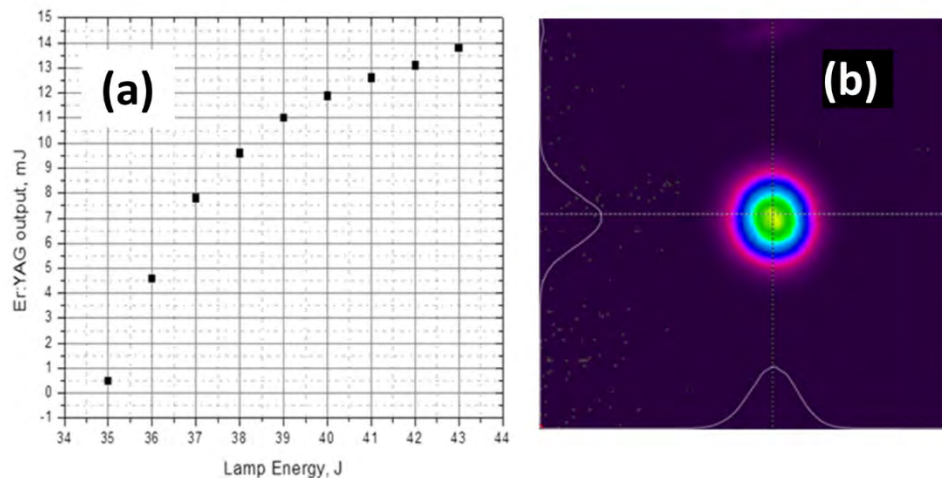


Fig. 3. (a) The output energy of Q-switched Er:YAG laser versus pump energy; (b) Er:YAG laser output beam profile at 40 J pump and 12 mJ output energies.

To control the output beam quality, we installed an intracavity aperture near the output coupler. The output energy dependence versus pump energy is depicted in Fig. 3(a). There was a roll-off from linear dependence for pump energy above 35 J and 10 mJ of output energy. The laser generates up to 17 mJ in a single pulse of 150 ns duration. The output laser beam profiles were measured by PyroCam III (Spiricon). The beam profile at 40 J pump (12 mJ output energy) is depicted in Fig. 3(b). The shape of the output beam does not feature any hot spot and was close to a Gaussian profile. This Er:YAG laser was used as a pump source for RT Fe:ZnSe laser in our further experiments.

3. Experimental characterization of tunable Fe:ZnSe laser

Polycrystalline Fe:ZnSe gain elements ($10 \times 5 \times 2 \text{ mm}^3$) were used for laser development. ZnSe doping was accomplished in a sealed vacuum ampoule by post-growth thermal diffusion of iron from metal films deposited on crystal grown by chemical vapor transport technique. The Fe^{2+} ion concentration was calculated from the absorption measurements and absorption cross section value $\sigma = 1.0 \times 10^{-18} \text{ cm}^2$ at $3.1 \text{ }\mu\text{m}$. The calculated concentration in the fabricated sample was measured to be $N = 1.5 \times 10^{19} \text{ cm}^{-3}$. A 2 mm thick gain element with an anti-reflection coating at pump wavelength and over 3.9-5.0 μm spectral range was used. The initial absorption at pump wavelength was 95%. Initially, the gain element was tested in a nonselective flat-flat cavity with 75% reflectivity of the output coupler. The maximum output energy was measured to be 5 mJ under 15 mJ of pump energy.

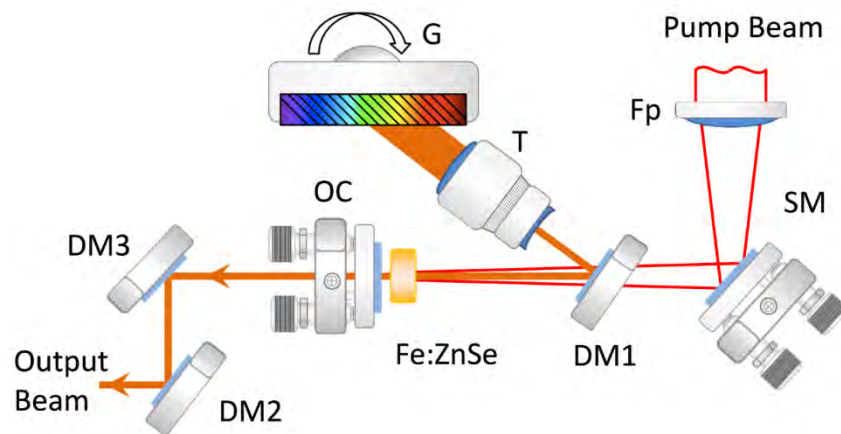


Fig. 4. Optical scheme of gain-switched Fe:ZnSe laser: OC- output coupler; DM- dichroic mirror; SM- pump steering mirror; T- intracavity lens telescope; G diffraction grating; Fp focusing lens.

The optical scheme of tunable Fe:ZnSe laser is shown in Fig. 4. We used a folded cavity design to avoid incidence of the pump radiation on the diffraction grating and to decrease the energy density on the folded mirror. The input dichroic mirror has >95% transmission at the pump wavelength and a high reflectivity over 3.5-5.0 μm spectral range. The same dichroic mirrors were used after output coupler to separate residual pump radiation and oscillation of Fe:ZnSe laser. To obtain a narrow line, tunable oscillation, the back mirror was replaced by a diffraction grating operating in Littrow mount auto-collimation regime with diffraction efficiency >80% in the first diffraction order. The major advantages of this scheme are in a stable direction of the output radiation during oscillation wavelength tuning and circularly-symmetric (non-astigmatic) output beam. Using zero order diffraction as an output and a highly reflective back mirror will increase the total efficiency of the laser but will introduce the astigmatism into the output beam as well as a spatial shift of the output beam under scanning of the oscillation wavelength. The intracavity telescope based on AR coated CaF_2 lenses was installed into the cavity to reduce the energy density on the diffraction grating and

to increase the grating resolving power. The output coupler has $\sim 70\%$ reflectivity over the Fe:ZnSe tuning range. The pump-focusing lens and steering mirror were used to control the pump area on the surface of the gain element.

The maximum output energy in dispersive cavity was measured to be 3 mJ. The tuning curve of the Fe:ZnSe laser under 11 mJ pump energy is shown in the Fig. 5(a). As one can see from the Fig. 5(a), the tuning range spans over 3.60-5.15 μm spectral range. A wide dip over the 4.2-4.4 μm spectral range is due to intracavity absorption by atmospheric CO_2 and can be mitigated by cavity purging with Ar or N_2 (curve ii). During the measurement, it was observed that the AR coating of the gain element was damaged by lasing at 4.5 μm , when output energy was higher than 2 mJ. We believe that it was due to the residual organic on the surface. Therefore, we skipped this region during the wavelength scanning in the purged cavity. The output linewidth was measured to be smaller than 1.5 nm over the whole range of tunability. Figure 5(b) depicts spectral line of the tunable laser at 4098 nm measured by Acton Research Corporation SpectraPro-300i monochromator with spectral resolution < 0.7 nm.

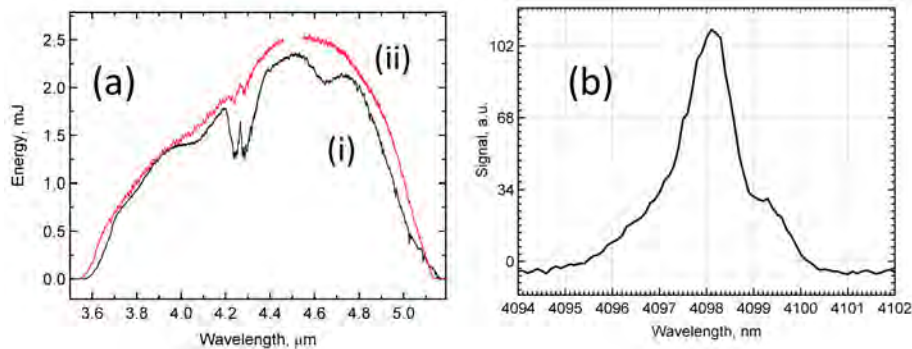


Fig. 5. (a) A characteristic tuning curve of the RT gain-switched Fe:ZnSe laser under 11 mJ pump energy and ambient condition (i), (ii) represents the same tuning curve of Fe:ZnSe laser with cavity purged with N_2 ; (b) Fe:ZnSe laser linewidth at 4098 nm.

The temporal profile of the Fe:ZnSe pulse at 4300 nm is shown in Fig. 6(a). The laser pulse consists of the sharp spike followed by a longer, ~ 50 ns, decay. The spike duration was smaller than 10 ns. It indicates a fast growth of the round-trip gain under pump radiation. It could be explained by a strong overlap of the emission and absorption spectra of Fe^{2+} ions at RT. In this case, the fast dynamic of the oscillation spectra results not only from the fast gain growth under the pump pulses but also due to the decrease of the absorption at the oscillation wavelength. The relative intensity of the spike is decreased with oscillation wavelength tuned to the edge of the tuning curve. The laser oscillates in TEM_{00} mode. The beam diameter at the output coupler and the output beam divergence at 4.4 μm were measured to be 3 mm and 5 mrad, respectively. The typical beam profile measured by PyroCam III is depicted in Fig. 6(b). The interference pattern in the pictures is due to interference on the input window of pyrocamera.

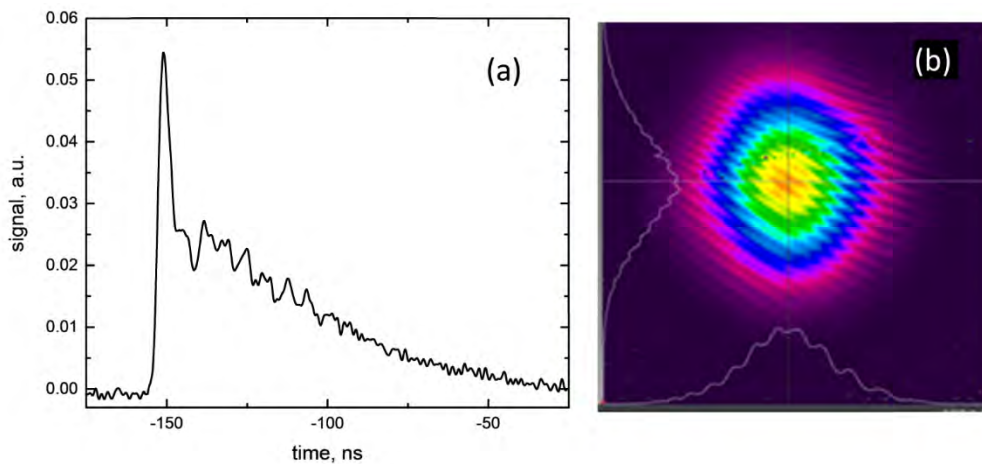


Fig. 6. Temporal (a) and spatial (b) profiles of the Fe:ZnSe pulse near 4300 nm.

Fe:ZnSe gain medium features a long upper level lifetime (55 μs over 77-140 K [21]) which is sufficient for high energy storage capability when pumped by a radiation of free running Er:YAG lasers. To test this approach, we used the same gain elements as were used for the gain-switched regime of operation. The optical scheme of Q-switched Fe:ZnSe laser is shown in Fig. 7. The Fe:ZnSe crystal was installed in a liquid nitrogen cryostat in these experiments. The non-selective laser cavity was formed by a flat high reflector and a flat OC with reflectivity 70% over 3.0-5.0 μm spectral range. The free running Er:YAG laser operating at 10 Hz repetition rate with a pulse duration of 200 μs was used for quasi-collinear pumping. The pump beam diameter at Fe:ZnSe gain element was measured to be ~ 3 mm. The rotating back mirror provided a mechanical Q-switching of the Fe:ZnSe laser cavity.

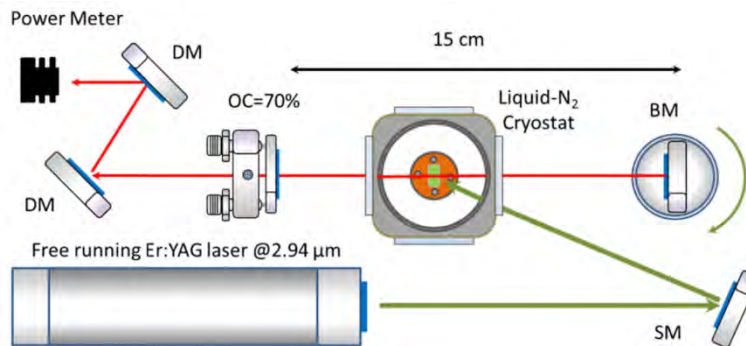


Fig. 7. Optical scheme of Q-switched Fe:ZnSe laser: OC- output coupler; BM- back mirror DM- dichroic mirror; SM- pump steering mirror.

In the free running regime, the slope efficiency of the Fe:ZnSe laser was measured to be $\sim 35\%$ with respect to the pump energy with lase threshold below 10 mJ. The spectrum of the Fe:ZnSe laser was centered at 4.15 μm and had bandwidth ~ 70 nm. Typical pulse duration of the Fe:ZnSe free-running lasers was usually within 150 μs pulse duration. The mechanical Q-switch based on rotation of back mirror was used in the experiments. Er:YAG free running laser was triggered at 10 Hz using approach described above for Q-switched Er:YAG laser. The rotation frequency was adjusted between 200 Hz and 600 Hz. The efficiency of the Fe:ZnSe laser with mechanical Q-switch was ~ 4 times smaller than in free-running mode. The maximum output energy in a single pulse of mechanically Q-switched Fe:ZnSe laser was measured to be ~ 3 mJ with a pulse duration of 150 ns. The output energy was several orders

of magnitude higher than the previously reported result for the Fe:ZnSe laser in passive Q-switch and CW pumping [22]. This output energy was not sensitive to rotation speed. An increase of the pump energy resulted in increase of the output energy but was accompanied by formation of multiple pulses. It should be noted that the gain element was not specifically optimized for the Q-switched regime of operation. The measured output beam diameter in the single pulse Q-switch regime was close to the diameter of the pump beam. If we assume that pumped area and oscillation mode sizes in the gain element were close to each other then we could use the pump beam diameter for laser efficiency estimations. The maximum possible accumulated energy in the pumped volume is proportional to the number of doped ions and was estimated to be ~12 mJ for the used gain element. Therefore, the measured maximum energy in a single pulse was ~25% from the maximum possible accumulated energy at 100% inversion of Fe ions. We believe that the further optimization of the laser cavity and the gain element could increase the accumulated energy as well as Fe:ZnSe output energy in a single pulse.

4. Conclusions

In summary, we report on RT gain-switched Fe:ZnSe lasers tunable over 3.60-5.15 μm pumped by a radiation of mechanically Q-switched Er:YAG laser operating at 2.94 μm . The maximum output energy was measured to be 5 mJ under 15 mJ of pump energy. We also demonstrated that Q-switched regime of oscillation could be effectively utilized for Fe:ZnSe lasers, however, it requires fabrication of a large-scale Fe:ZnSe gain elements. This approach could be attractive for development of a high-energy short-pulse solid-state mid-IR systems operating over 3.6-5.2 μm spectral range.

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Disclosures

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