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Fibre coupled $Hg_{1-x}Cd_xTe$ detectors

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Abstract

Fibre-coupled mercury–cadmium telluride $Hg_{1-x}Cd_xTe$ (MCT) high performance infrared radiation (IR) detectors have been developed and fabricated. This new product is originated from 25 years experience of MCT detectors and IR fibre optics technologies. The product includes single- and multi-element detectors designed for registration of optical signals in wide-band and narrow-band mode in spectral range from 2 to 18 μm. Detectors are manufactured in an integrated or modular design and include MCT optical sensors, optical couplers and fibre pig-tails or cables. Registered infrared radiation is delivered to the sensitive area of the detector through either chalcogenide IR-glass (CIR-) fibre (2–6 μm) or polycrystalline infrared (PIR-) fibre (4–18 μm). The unique feature of $Hg_{1-x}Cd_xTe$ alloys enables tuning spectral responsivity of the detector element for the ordered spectral range.

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1. Introduction

Optical sensors and/or fibres are integral parts of almost every state-of-the-art solid-state infrared opto-electronic device or system. Progress in mercury–cadmium telluride (MCT) detectors and infrared radiation (IR) fibre optic technologies has enabled development and fabrication of advanced opto-electronic components and systems for the detection and processing of infrared radiation for the spectral range greater than 1.5 μm. These are traditionally divided as short-wave (SWIR) ranging from 1.5 to 2.5 μm, mid-wave (MWIR) from 3.0 to 5.5 μm, long-wave (LWIR) from 8.0 to 14.0 μm and very long-wave (VLWIR) from 14.0 to 20.0 μm.

Research groups and the industrial community are seriously interested in affordability of real-time non-contact optical metering systems for characterising different solid, liquid or gas objects, which are difficult to access or beyond direct optical access [1]. Systems based on fibre coupled IR detectors measuring the in situ local intensity of radiation, emitted, reflected or absorbed by objects, can solve such problems.

Now reliable industrial level products can be offered: fibre coupled MCT detectors. In Russia the technology of MCT IR sensors and IR fibres (essential components of the new product) originate from the scientific schools of Kurbatov [2] and Prokhorov [3–6], respectively. Additionally there are other groups related to MWIR/LWIR fibres mostly involved in research work [7,8].

2. MCT alloys and IR sensors

Solid ternary alloys mercury–cadmium telluride or $Hg_{1-x}Cd_xTe$, where composition x is a mole fraction of CdTe, form a continuous series of alloy compositions. Energy gap $E_g(x, T)$ [9,10] is varied almost linearly from 0.0 to 1.6 eV on the semiconductive side of $Hg_{1-x}Cd_xTe$ when x is varied in the range $0.14 \leq x \leq 1.0$. A wide range of IR sensors, based on MCT bulk material or epitaxial structures, can be fabricated.

The conventional series of MCT IR sensors include

- sensors assembled on the base of a dewar filled by liquid nitrogen.

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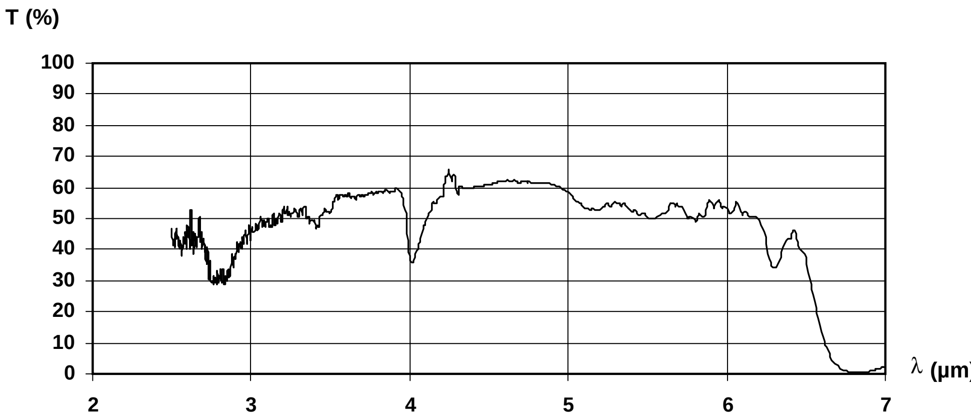

Fig. 1. Spectral transparency of 1 m long CIR-fibre with core diameter 1000 μm (absolute percentage).

- single- and multi-element sensors provided with Joule–Thomson micro-liquidizer or Stirling-cycle cooler. The above-mentioned items can be fabricated as either photoconductive (PC) or photovoltaic (PV) with a peak responsivity wavelength λ_p from 3 to 20 μm. Detectivity $D^*(\lambda_p)$ values are limited by background flux density fluctuations (BLIP) at the operation temperature of the sensitive element $T_{op} = 78\,K$ so that $D^*(\lambda_p = 4\,\mu m) \approx 3.5 \times 10^{11}\,cm\,Hz^{1/2}\,W^{-1}$ (Jones), $D^*(\lambda_p = 10.6\,\mu m) \approx 1.0 \times 10^{11}$ Jones, $D^*(\lambda_p = 15\,\mu m) \approx 1.0 \times 10^{10}$ Jones and $D^*(\lambda_p = 18\,\mu m) \approx 1.0 \times 10^{9}$ Jones.
- sensors with thermoelectric (TE) cooling (1-, 2-, 3- or 4-stage TE cooler) are very convenient and require for operation electricity only. TE cooled sensors can be fabricated either PC or PV. Performance can be optimised at every λ_p from ≈2 to ≈10 μm. $D^*(\lambda_p)$ value is limited by the fundamental properties of $Hg_{1-x}Cd_xTe$ ($x \approx 0.18$–0.52) semiconductive material at $T_{op} = 195$–$253\,K$. PV MCT sensors are effective for λ_p from ≈2 to ≈5 μm; PC MCT—for λ_p from ≈3 to ≈10 μm. Typical values of $D^*(\lambda_p)$ of TE3 cooled PC MCT sensors (T_{op} near 210 K) equal to $D^*(\lambda_p = 3\,\mu m) \approx 1.0 \times 10^{11}$ Jones, $D^*(\lambda_p = 4.5\,\mu m) \approx 5.0 \times 10^{10}$ Jones, $D^*(\lambda_p = 8\,\mu m) \approx 5.0 \times 10^{8}$ Jones and $D^*(\lambda_p = 10\,\mu m) \approx 2.0 \times 10^{8}$ Jones.

3. IR-fibres based on chalcogenide glasses and solid solutions of silver halide crystals

IR transmitting materials for the spectral range from 2 to 20 μm are well known at least last 45 years [11]. Many years' research and development of IR fibres technologies for MWIR and LWIR/VLWIR spectral ranges led finally to the selection of proper base materials, forming of perspective IR fibre design concept and to the development of effective manufacturing technology to meet customer requirements [3–6]. Nowadays there are two basic IR fibres for MWIR and LWIR/VLWIR spectral ranges available: CIR-fibres (chalcogenide infrared glass fibres) and PIR-fibres (polycrystalline infrared fibres). Chalcogenide infrared glasses based on arsenic trisulfide glass (As_2S_3) are the most pure optical glasses for transmission of radiation in the spectral range from 1.5 to 5–6 μm. The transmission spectrum of a CIR-fibre is presented on Fig. 1. The CIR-fibre is a fibre with core/clad integral structure formed by CIR glass compositions with different refractive indexes. Refractive index changes stepwise at core/clad interface. To enhance the mechanical strength of brittle CIR glass a special double polymer layer coats the CIR-fibre lateral surface. This layer improves CIR-fibre flexibility and provides mechanical protection. CIR-fibre fabrication is possible either by drawing from crucible dies or by drawing from a

Table 1
Typical specifications of CIR- and PIR-fibre cables

Order number	Parameter name	Typical value	
		CIR-fibre cables	PIR-fibre cables
1	Transmission range	From 2.0 to 6.0 (μm)	From 4.0 to 18.0 (μm)
2	Core/clad structure materials	Chalcogenide glasses As_2S_3/As-S (amorphous)	Ternary solid solutions AgCl:AgBr (polycrystalline)
3	Core/clad diameter	200–700/300–850 (μm)	400–900/500–1000 (μm)
4	Core refractive index	2.4	2.1
5	Optical losses	0.2 dB/m at wavelengths 2–4 (μm)	0.2–0.3 dB at wavelength 10.6 (μm)
6	Ambient temperature range for operation	From 280 to 400 (K)	From 5 to 523 (K)
7	Maximum length of cable available	Up to 20–50 meters	Up to 20–30 meters

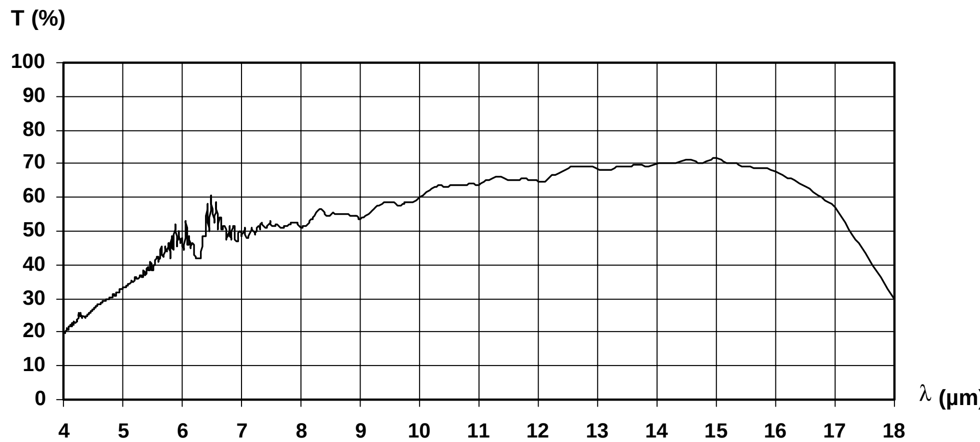

Fig. 2. Spectral transparency of 1 m long PIR-fibre with core diameter 1000 µm (absolute percentage).

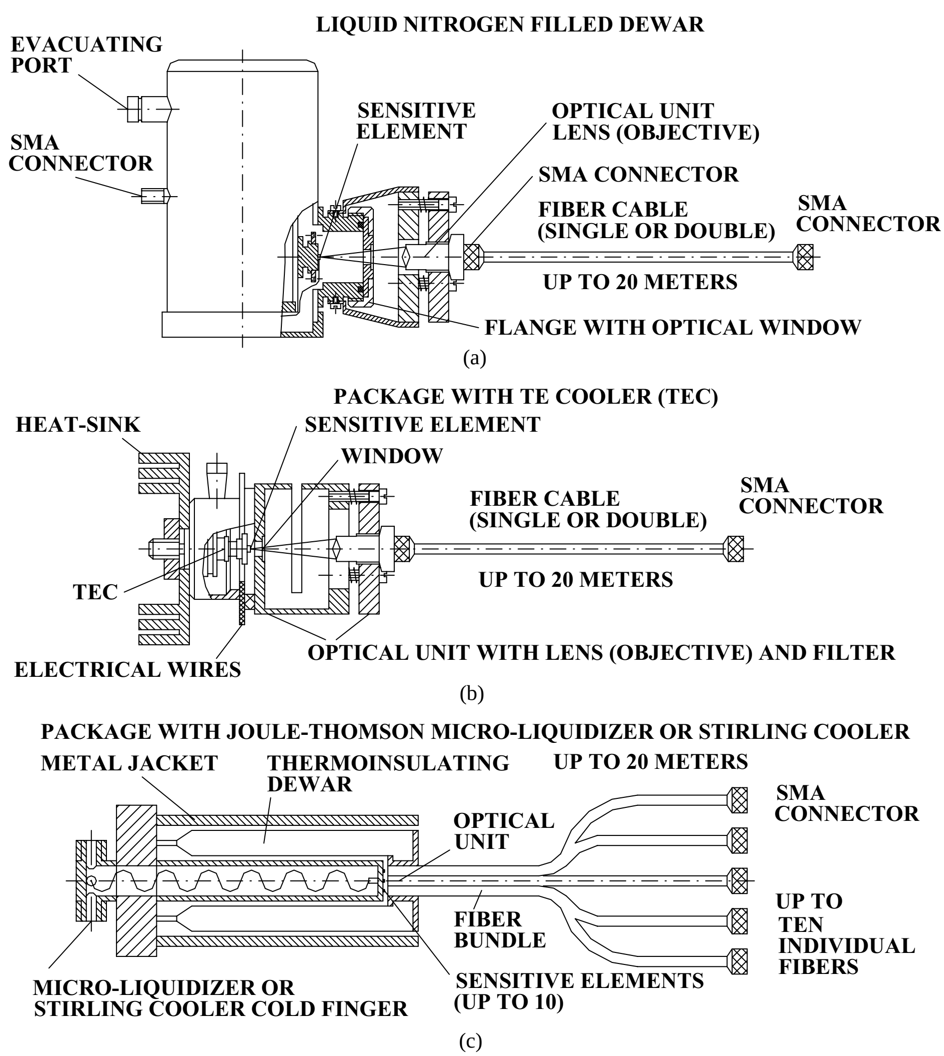

Fig. 3. Design concept of fibre coupled MCT infrared radiation detectors: (a) and (b): design with outside detachable optical coupler and (c): design with fixed optical coupler.

proper preform. A typical specification of the CIR-fibres is presented in the Table 1.

Silver halide crystals AgCl:AgBr are solid solutions of two binary compounds AgCl and AgBr in different ratios. In contrast to most other infrared crystals AgCl:AgBr crystals are not toxic, non-hygroscopic and allow plastic deformation under high pressure. These unique features in synergy with excellent optical purity of silver halide crystals enable manufacturing of high-quality IR fibres for LWIR/VLWIR and partly MWIR spectral ranges from 4 to 18 μm. The transmission spectrum of the PIR-fibre is presented on Fig. 2. The PIR-fibre is a fibre with core/clad integral structure formed by ternary solid solutions AgCl:AgBr with different refractive indexes. Refractive index changes stepwise at core/clad interface. The basic fabrication method is extrusion with plastic deformation of proper core/clad preform in vacuum. After extrusion PIR-fibres are inserted into loose PolyEtherEtherKetone (PEEK) tubing to provide mechanical protection and elastic bending. No polymer coating is used directly on the fibre's lateral surface. PEEK tubing prevents PIR-fibres from illumination by UV-Visible light and hence the formation of photo-induced silver on the fibre's surface. PIR-cables are very durable and applicable in a wide temperature range from 5 to >500 K without deterioration of parameters. The typical specification of the PIR-fibres is presented in the Table 1.

4. Design concept of fibre coupled detectors

The high-sensitive MCT IR detector set includes a cooling system, which provides proper operation temperature of the sensitive element(s) (Section 2). Therefore the sensitive element(s) are mounted on a cooled header within a vacuum-sealed container. The container can be vacuumed or filled with a gas of low thermal conductivity or a dry gas. The IR sensor with cooling system is carefully balanced in respect to heat flows which guarantees the required level of operating temperature and hence a high level of opto-electronic performance. Effective design of a fibred detector is a compromise between the necessity not to break the thermal balance around the sensitive element and a desire to collect as much as possible of the optical signal power irradiated from butt-end of fibre. To meet the first requirement direct contact between the butt-end plane of fibre and front plane of the sensitive element is totally avoided. Therefore the use of an outside optical coupler capable of collecting a diverged radiation beam and to direct it precisely onto the active area of the sensitive element within the sealed container is the solution to the problem. Minimal levels of optical losses should be obtained. For this concern we implement the two basic design concepts presented on Fig. 3.

- A design with an autonomous MCT IR sensor and separate outside optical coupler (Fig. 3a and b). An optical coupler including lens (objective) is attached onto the sensor container and it is changeable. The fibre cable is connected via an optical SMA connector.
- A design with an IR sensor and optical coupler fixed after proper tuning (Fig. 3c). In this case the optical coupler becomes an integral part of the fibred detector and cannot be changed. The concept can be realised with MCT IR sensors equipped with an autonomous thermo-insulating dewar as an integral part of the package.

5. Fibred detectors performance

Different MCT fibred detectors were fabricated and tested. These detectors were TE cooled detectors for operation in the MWIR (3.0–5.5 μm) spectral range (Fig. 4) and dewar type detectors for operation in LWIR (8–14 μm) spectral range. A few detectors were provided additionally by narrow band-pass filter to detect the intensity of radiation absorbed within narrow (known in advance) absorption lines of different gases. For example, TE cooled detectors were provided by proper narrow band-pass filters to detect the radiation intensity within the absorption line of methane (3.25 μm) and hydrocarbons (3.43 μm).

Generally speaking performance and behaviour of fibre coupled MCT IR detectors is very similar to normal MCT IR detectors. The $D^*(\lambda_p)$ value of fibred detectors was 2–5 times lower than the initial one (Section 2) due to optical losses caused by reflection and divergence of the radiation beam but this is not an extraordinarily high level of signal power losses. Optical losses up to 50% (two times) are not considered critical in systems with normal IR detectors. The

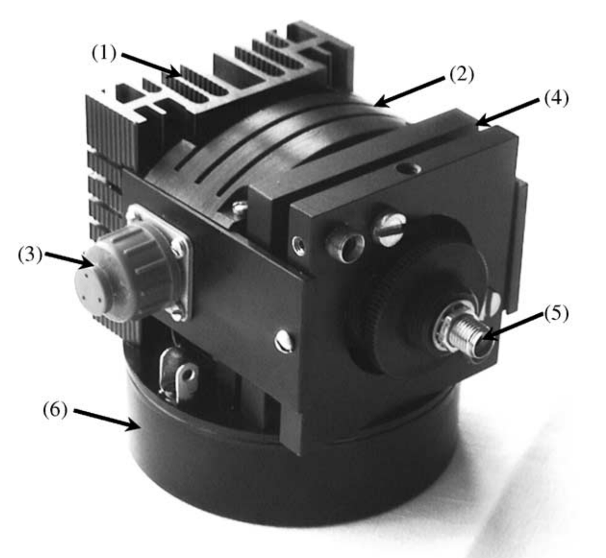

Fig. 4. Miniaturized fibred MCT photo-receiver: (1) heat-sink; (2) case containing PC MCT MWIR TE cooled sensor and plate with changeable filter (option); (3) electrical connectors on both sides of the case; (4) optical coupler with optical SMA connector; (5); and (6) preamplifier box. IR-fibre cable is detached. Overall dimensions: length, 87.5 mm; width, 76.0 mm; height, 70.5 mm.

use of ultimate performance MCT IR sensors will enable the manufacturing of fibre coupled MCT IR detectors with an opto-electronic performance met almost every practical customer's need.

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