New IR-detectors pig-tailed with IR-fibers

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ABSTRACT

New generation of Mercury-Cadmium-Telluride (MCT) high performance infrared radiation (IR) detectors with IR-fiber input has been developed and fabricated. This new product is originated from 25 years experience in MCT detectors and IR fiber optics technologies. Range of products includes single- and multi-element detectors designed for registration of optical signals in spectral range from 2 to 18 μm. Detectors design is integrated or modular and includes package, sensitive element, cooling system, operating temperature sensor, optical components such as narrow band-pass filter and/or lens and/or different kind of optical window, optical connection unit and fiber pig-tail or fiber cable. Cooling system options include thermoelectric cooler, long-holding time dewar filled with liquid nitrogen, Joule-Thomson micro-liquidizer and Stirling-cycle cooler. Registered infrared radiation is delivered to sensitive area of detector through either Polycrystalline InfraRed (PIR-) Fiber (4 - 18 μm) or Chalcogenide IR-glass (CIR-) Fiber (2 - 6 μm). Unique feature intrinsic to $Hg_{1-x}Cd_xTe$ (MCT) alloys to form continuous series of alloy compositions "x" with proportionally changed energy gap $E_g(x, T)$ allows to tune spectral responsivity of detector sensitive element with ordered spectral range and hence to use every time the highest sensitive detector.

Keywords: solid solutions, HgCdTe IR radiation detectors, IR-fibers, light absorption, transmission and reflection

1. INTRODUCTION

Optical radiation detectors and fibers are essential parts of almost every state-of-the-art opto-electronic system. As usual detectors' sensitive elements and fibers are based on high-quality single-crystal or polycrystalline or amorphous materials, which are mostly alloys and compounds. Real progress in manufacturing technology of alloys and compounds provides good opportunity to create new generation of opto-electronic components and systems. All above-mentioned statements are related directly to opto-electronic components and systems designated for detection and processing of infrared radiation (IR) in the spectral range longer than 1,5 μm traditionally divided on Short-Wave (SWIR) range from 1,5 to 2,5 μm, Mid-Wave (MWIR) range from 3,0 to 5,5 μm, Long-Wave (LWIR) range from 8,0 to 14,0 μm and Very Long-Wave (VLWIR) range from 14,0 to 20,0 μm. There was in the past, there is nowadays and there will be in the future a great interest in creation of real-time non-contact optical metering systems to characterize objects by emitted or reflected or absorbed infrared radiation with wavelength longer than 1,5 μm, which are difficult of access or beyond direct optical access [1].

Those objects are different gases, organic and non-organic liquid and solid substances, coherent and non-coherent sources emitting radiation within narrow spectral lines, heated objects emitting thermal radiation according to those local temperatures. For example, measured parameters could be local surface temperature of different parts of airplane or ship or train equipment having no direct optical access or concentration of harmful gas in remote cavity or local wall temperature in narrow long bent tube, for example, in industrial borescopy or medical endoscopy. That special real-time non-contact optical metering system can be developed and operates effectively if and any there are high performance infrared radiation sensor and high-quality reliable low optical loss infrared fiber both tuned to ordered spectral range (line). Effective operation of the system is required proper conjunction between detector's sensitive element and fiber.

Now we are in position to offer new high-tech product: MCT detectors with IR-fiber input. Those detectors are

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reliable industrial level products. In Russia MCT IR sensors as a part of new product were originated first from scientific school founded by Russian Academician-by-correspondence Mr. Leonid Kurbatov [2] and IR fibers were originated first from scientific school founded by Russian Academician Nobel Prize Winner Mr. Alexander Prokhorov [3-6].

2. MCT ALLOYS AND IR DETECTORS

Solid ternary alloys Mercury-Cadmium Telluride or MCT are alloys of two binary compounds HgTe and CdTe. Chemical formula is $(HgTe)_{1-x}$ + $(CdTe)_x$ = $Hg_{1-x}Cd_xTe$, where composition "x" is mole fraction of CdTe. Some unique features are inherent to $Hg_{1-x}Cd_xTe$ alloys. First, $Hg_{1-x}Cd_xTe$ forms continuous series of alloy compositions "x" with proportionally changed energy gap $E_g(x,T)$ [7, 8]. Energy gap $E_g(x,T)$ is varied almost linearly from 0,0 to 1,6 eV on semiconductive side of $Hg_{1-x}Cd_xTe$ when "x" is varied in the range $0{,}14 \le x \le 1{,}0$. Second, there is a possibility to grow uniform, high purity and crystalline perfect $Hg_{1-x}Cd_xTe$ material in whole range of "x" from 0,0 to 1,0 with optimal electro-physical, electro-optical and other properties, which are needful to manufacture high quality infrared radiation sensors in the range from 1,5 to 20 µm. Above-mentioned features of MCT material make it possible to fabricate a wide nomenclature of infrared radiation detectors with excellent sensitivity and attractive applicability.

Conventional series of MCT IR sensors include:

– Detectors based on dewar filled by liquid nitrogen. Availability of miniaturized dewars with holding time from 5 to 24 hours gives cost-effective opportunity for much number of research and industrial applications.

– Single- and multi-element detectors provided with Joule-Thomson micro-liquidizer or Stirling-cycle cooler. Those detectors can operate in autonomous or semi-autonomous mode for a long period of time. Such sensors are used often in severe conditions of exploitation.

Dewar type detectors and detectors provided with Joule-Thomson micro-liquidizer or Stirling-cycle cooler can be fabricated either photoconductive (PC) or photovoltaic (PV) covering MW & LW spectral ranges from 3 to 20 µm. Detectivity $D^*(\lambda_p)$ values are limited by background flux density fluctuations (BLIP) at operation temperature of sensitive element 78 K so that $D^*(\lambda_p{=}4{,}0\ \mu m) \approx 3{,}5E{+}11\ cmHz^{1/2}W^{-1}$ (Jones), $D^*(\lambda_p{=}10{,}6\ \mu m) \approx 1{,}0E{+}11$ Jones, $D^*(\lambda_p{=}15{,}0\ \mu m) \approx 1{,}0E{+}10$ Jones and $D^*(\lambda_p{=}18{,}0\ \mu m) \approx 1{,}0E{+}09$ Jones.

– Detectors with thermoelectric (TE) cooling (1- or 2- or 3- or 4-stage thermoelectric cooler) are very convenient opto-electronic components for creation of control and metering equipment due to high performance, reliability and simplicity in exploitation, which requires electricity only. TE cooled detectors can be fabricated either PC or PV with every value of peak responsivity wavelength λ_p in the spectral range from ≈ 2,0 to ≈ 10,0 µm. This fact allows to optimize performance of detector at every required value of λ_p and to reach value of detectivity $D^*(\lambda_p)$ limited by fundamental properties of $Hg_{1-x}Cd_xTe$ (x ≈ 0,18 – 0,52) semiconductive material at T_{op} = 195 – 253 K. PV MCT detectors with thermoelectric cooling are effective for λ_p from ≈ 2,0 to ≈ 5,0 µm; PC MCT – for λ_p from ≈ 3,0 to ≈ 10,0 µm. Typical values of peak detectivity of TE3 cooled PC MCT sensors (operation temperature near 210 K) are as follows: $D^*(\lambda_p{=}3\ \mu m) \approx 1{,}0E{+}11\ cmHz^{1/2}W^{-1}$ (Jones), $D^*(\lambda_p{=}4{,}5\ \mu m) \approx 5{,}0E{+}10$ Jones, $D^*(\lambda_p{=}8{,}0\ \mu m) \approx 5{,}0E{+}08$ Jones and $D^*(\lambda_p{=}10{,}0\ \mu m) \approx 2{,}0E{+}08$ Jones.

3. IR-FIBERS BASED ON CHALCOGENIDE GLASSES AND SOLID SOLUTIONS OF SILVER HALIDE CRYSTALS

IR transmitting materials for spectral range from 2 to 20 µm are well known at least last 45 years [9]. But only a few materials do have properties necessary for manufacturing uniform long-length IR fibers with stable optical performance and attractive applicability features.

Many years development and studying of IR fibers technologies for MW & LW spectral ranges led to final selection of proper base materials, forming of perspective IR fiber design concept and creation of effective manufacturing technology coping to customer requirements [3-6].

Nowadays there are available two basic types of IR fibers for MW & LW spectral ranges: CIR-fibers (Chalcogenide InfraRed glass fibers) and PIR-fibers (Polycrystalline InfraRed fibers).

Chalcogenide InfraRed glasses based on arsenic trisulfide glass (As_2S_3) are the most pure optical glass for transmission range from 1.5µm to 5-6µm. Spectral transmitting curve of CIR-fiber is presented on Fig. 1. Design concept is step refractive index structure with Numerical Aperture NA=0.3-0.37 defined by refractive indexes difference for Core/Clad glass compositions. To enhance mechanical strength of brittle CIR glass its lateral surface is coated by special double polymer layer, which enable CIR-fiber flexibility and mechanical protection. CIR-fiber fabrication is possible either by drawing from crucible dies and by drawing from the correspondent preform. Typical specification of CIR-fibers is presented in Table 1.

Solid solutions of Silver Halide crystals AgCl:AgBr are solid solutions of two binary compounds AgCl and AgBr in different ratio. In difference with the most 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 solid solutions enable to use those for manufacturing of high-quality IR fibers for LW and MW spectral ranges by extrusion method. Spectral transmitting curve of PIR-fiber is presented on Fig. 1. Design concept is step index structure defined by difference in refractive indexes of Core/Clad preform. PIR-fiber is fabricated by plastic deformation of proper Core/Clad preform in vacuum. After extrusion PIR-fibers are inserted into loose PolyEtherEtherKetone (PEEK) tubing for mechanical protection enabling very elastic bending, while no polymer coating is used directly on lateral fiber surface. PEEK tubing provides in addition PIR-fiber protection against illumination by UV-Visible light – to prevent photo-induced Silver formation on fiber's surface and could be also used for hermetic PIR-fiber cable assembly. To prevent chemical interaction of Silver Halides with metals more active than Silver – the special connectors are used for cable assembly. SMA-connectors, for example, are made from Titanium or PEEK-material. Proper fiber manufacturing and assembly technology result in PIR-cables which very durable and can be used in a wide temperature range from 5 K to >500 K without deterioration of those parameters. Industrial level PIR-cables sustain also to specific climatic and vibration tests. Typical specification of PIR-fibers is presented in Table 1.

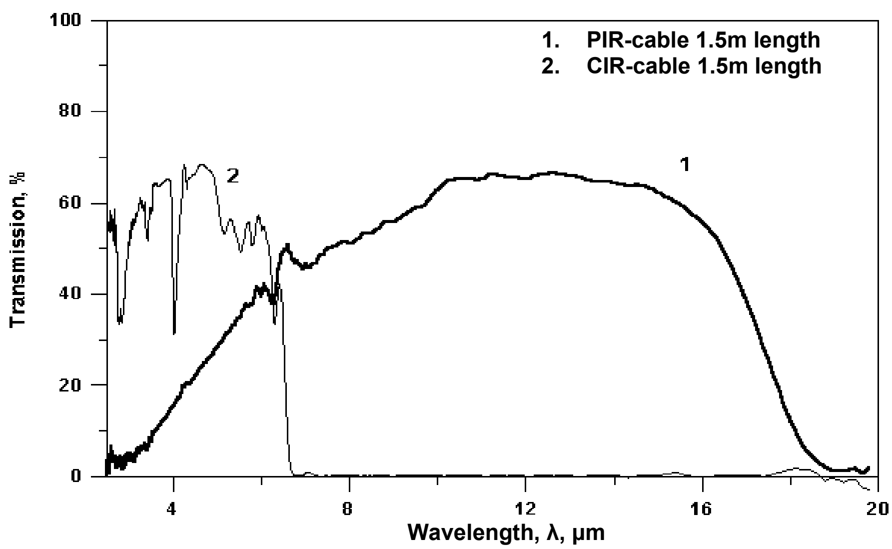

Fig.1. Typical transmission spectra of CIR-fiber cable 750/850 μm Core/Clad diameters and PIR-fiber cable 900/1000 μm Core/Clad diameters both with length of 1,5 meter

Table 1: Typical specification of CIR- and PIR-fiber cables

Ord. No.	Parameter Name	Typical value	
		CIR-fiber cables	PIR-fiber cables
1	**2**	**3**	**4**
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 solution 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	Max length of cable available	Up to 20-50 meters	Up to 20-30 meters

4. DESIGN CONCEPT OF FIBERED DETECTORS

High-sensitive MCT IR detectors include in set cooling system, which provides proper operation temperature of sensitive element(s) (see Chapter 2). Therefore sensitive element(s) are mounted on cooled header within vacuum tight sealed package. Package cavity can be under vacuum of filled by low thermal conductivity gas or dry gas. IR detector with cooling system is carefully balanced in respect to heat flows to cooled header that guarantees required level of operation temperature and hence high level of opto-electronic performance. Effective design of fibered detector is compromise between necessity do not break thermal balance around sensitive element and desire to collect as much as possible of optical signal power irradiated from butt-end of fiber. For the first reason direct intimate contact between butt-end plane of fiber and front plane of sensitive element is excluded absolutely. Taking into account second provision it is desirable to use outside optical adjustment unit with capability to collect of diverged radiation beam and to direct it precisely onto active area of sensitive element within sealed package. Minimal level of optical losses should be got. In this concern we implement two basic design concepts presented on Fig. 2:

– Design with autonomous MCT IR detector and separate outside optical adjustment unit (Fig. 2 a and b). Optical unit including lens (objective) and optionally changeable optical filter is fixed on sensor package. Connection of fiber to sensor is provided via optical SMA type connector. In this case MCT IR sensor can be used separately as normal IR detector. Optical adjustment unit is changeable.

– Design in which IR detector and optical adjustment unit are coupled after proper tuning (Fig. 2 c). In this case optical adjustment unit become integral part of fibered detector and cannot be changed. This design concept can be realized in MCT IR detectors which package includes autonomous thermo-insulating dewar as integral part of package.

5. FIBERED DETECTORS PERFORMANCE

Different MCT fibered detectors were fabricated and tested. Those detectors were TE cooled detectors for operation in MWIR (3,0-5,5 μm) spectral range (Fig. 3) and dewar type detectors for operation in LWIR (8,0-14,0 μm) spectral range. A few detectors were provided additionally by narrow band-pass filter to detect 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 radiation intensity within absorption line of methane (3,25 μm) and hydrocarbons (3,43 μm).

Generally speaking performance and behavior of fibered MCT IR detectors is very similar to normal MCT IR detectors. $D^*(\lambda_p)$ value of fibered detectors was 2-4 times lower that initial one (see Chapter 2) due to optical losses caused by reflection and divergence of radiation beam. But this is not extraordinary high level of signal power losses. Optical losses up to 50% (2 times) are considered as not critical in conventional systems with normal IR detectors. Using of ultimate performance MCT IR detectors as a part of fibered detectors will allow manufacturing MCT IR fibered detectors with opto-electronic performance acceptable for almost every practical need of customer. Thus TE-cooled MCT detectors with peak responsivity through whole MWIR range from 3 to 5,5 μm (Fig. 4) being coupled with CIR-fibers will easy cope customer needs in detection of radiation emitted by objects with temperature from 400 K to 600 K (Fig. 5). Properly cryogenically MCT detectors with peak responsivity through whole LWIR range from 8 to 14 μm (Fig. 6) being coupled with PIR-fibers will easy cope customer needs in detection of radiation emitted by objects with temperature from 200 K to 400 K (Fig. 7).

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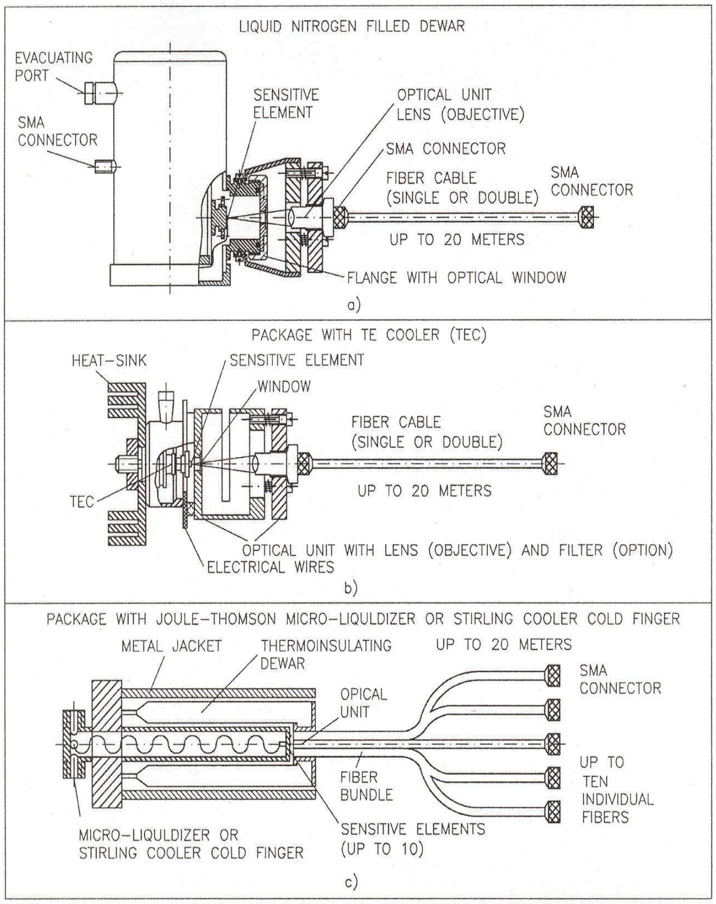

Fig.2. Design concept of MCT infrared radiation detectors with fiber input:
a) and b) – design with outside detachable optical coupler and c) – design with fixed optical coupler

Fig 3. Miniaturized fibered MCT photo-receiver: (1) – heat-sink; (2) case containing PC MCT MWIR TE cooled detector, plate with changeable filter and focusing lens, (3) – electrical connectors on both sides of the case; (4) – adjustable optical unit with optical SMA connector; (5) – optical fiber cable and (6) – preamplifier box. Overall dimensions: Length x Width x Height – 87,5 x 66,0 x 70,5 mm

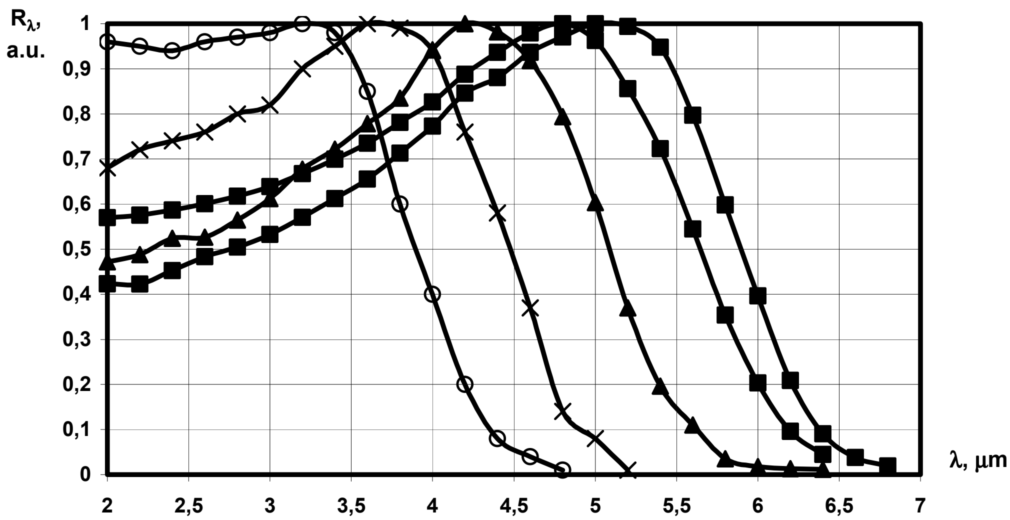

Fig. 4. Typical spectral responsivity curves of thermoelectrically cooled MCT photoconductive infrared detectors. Spectral response is varied with MCT composition "x" and is optimal for coupling with CIR-fibers

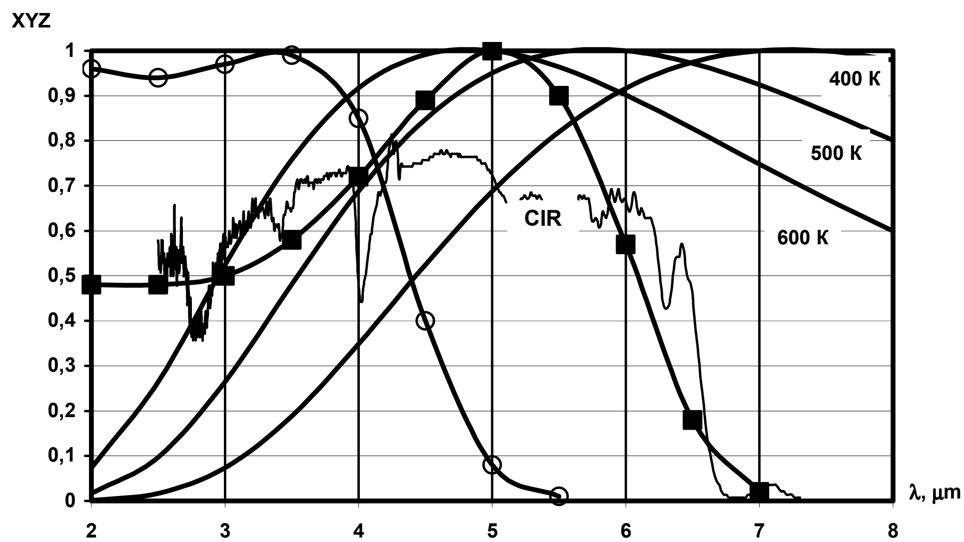

Fig. 5. "X" – normalized photon power radiant flux density (black body T = 400, 500 and 600 K); "Y" – spectral responsivity curves of Mid-Wave MCT detectors; and "Z" – spectral transparency of 1 meter long CIR fiber with core diameter 1000 μm (absolute value)

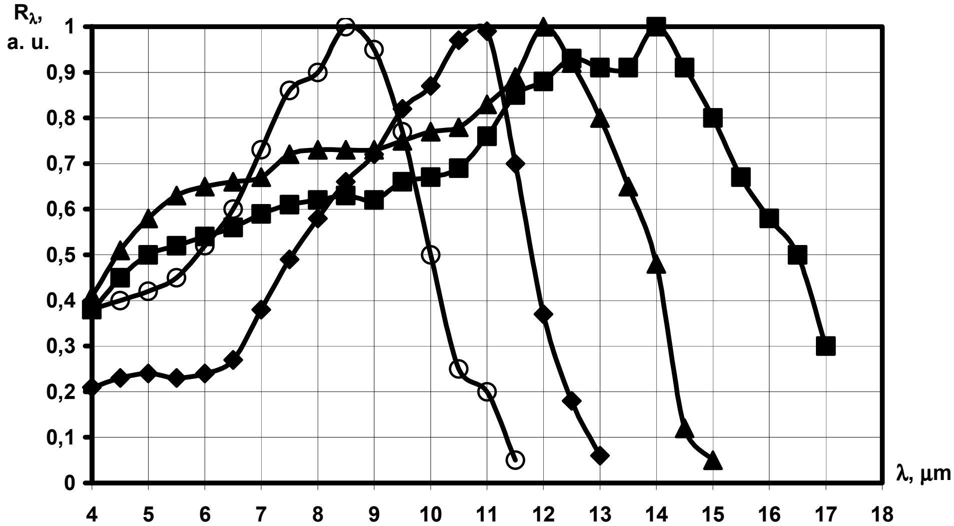

Fig. 6. Typical spectral responsivity curves of liquid nitrogen cooled fast MCT photoconductive infrared detectors. Spectral response is varied with MCT composition “x” and is optimal for coupling with PIR-fibers

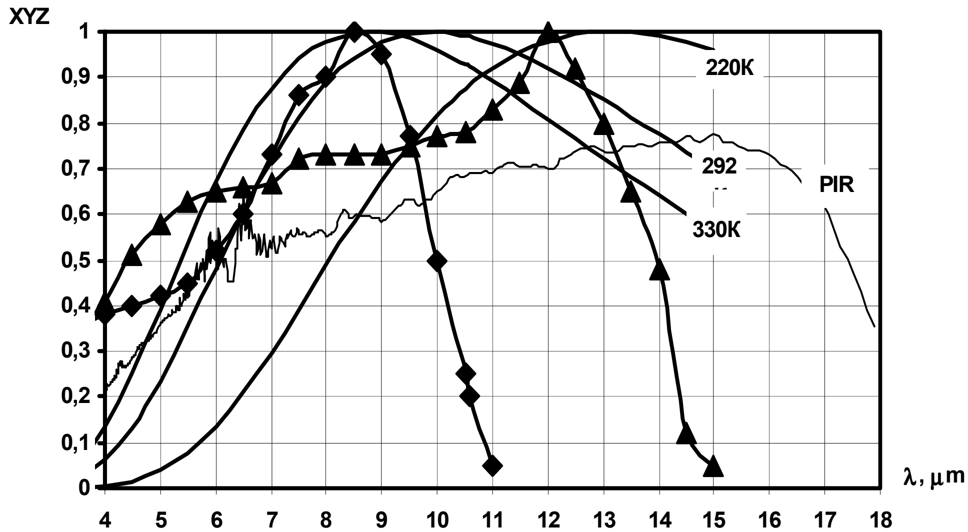

Fig. 7. “X” – normalized photon power radiant flux density (black body T = 220, 292 and 330 K); “Y” – spectral responsivity curves of Long-Wave MCT detectors; and “Z” – spectral transparency of 1 meter long PIR fiber with core diameter 1000 μm (absolute value)