Infrared Detection Module for Free Space Optics

Marcin Ratajczyk\textsuperscript{1}, Ryszard Paliwoda\textsuperscript{1}, Maciej Rzeczkowski\textsuperscript{1}, Waldemar Gawron\textsuperscript{2}, Jarosław Pawluczyk\textsuperscript{1}, and Józef Piotrowski\textsuperscript{1}

\textsuperscript{1}VIGO System S.A., 05-850 Ozarow Mazowiecki, 129/133 Poznanska str., Poland
\textsuperscript{2}Institute of Applied Physics, Military University of Technology, 2 Kaliskiego Str., Warsaw 00-908, Poland

Abstract — Free space optics (FSO) communication in LWIR range is less sensitive to atmosphere features. VIGO System S.A. — company from Poland — develops high performance detector module optimized for LWIR range. We present new detection module dedicated to open space optical communication optimized for 10 µm.

Module specification:
- Detector: PVI-2TE-10 photodiode with immersion lens, thermoelectrically cooled.
- Operating temperature range: \(-30\ldots+60^\circ\text{C}\).
- Detector temperature stabilization precision: 0.01\(^\circ\text{C}\).
- Detector time constant: < 1 ns.
- Preamplifier bandwidth: 100 MHz.
- Input current noise: 5 pA/\sqrt{Hz}.
- Detector capacity < 5 pF.

Detection module is based on PVI-2TE-10 HgCdTe photodiode, thermoelectrically cooled by two stage Peltier cooler. It is optimized for long wavelength — 10 µm. TEC controller stabilizes detector temperature with high precision in wide ambient temperature range. Immersion lens enables optimization of the detector physical dimensions, decreasing detector capacity and time constant.

Module parameters enable maximum transmission speed 100 Mb/s. Low bit error rate requires correct transmission with low and high signal level. Detector and preamplifier have wide linear working range, noise optimization provides module high detectivity. DC reverse bias increases dynamic resistance and improves frequency response.

1. INTRODUCTION

A new trend in the development of broadband free-space optical communication is the application of long-wave infrared radiation (8–14 µm) \cite{1–4}. The main advantage of this solution is decreased radiation scattering in aerosols and dusts.

Until recently, the lack of suitable radiation sources and detectors constituted the main problem area. The existing devices were expensive and not user-friendly. It appears that the problem of radiation sources may soon be solved by the development of quantum cascade lasers \cite{5}.

Uncooled photodetectors of long-wave infrared radiation are also currently under development. The main requirements for long-wave detectors for free-space optical communication are as follows:

\textit{High sensitivity}. High sensitivity is necessary to achieve low error ratio using low laser beam power and in small-aperture optics. In practice, performance close to fundamental limits are required \cite{6}.

\textit{High operation speed}. Subnanosecond response time is typically required for the present optical links.

\textit{Other requirements}. Detectors should be convenient in use, reliable, and inexpensive. The size of the active element should be comparable to the beam spot size in the focal plane of the optical system. Large variation in the radiation power results in a requirement of adequately wide range of linear responsivity.

The requirements of high sensitivity and speed were met by HgCdTe photodiodes available as early as the 1970’s. However, such devices required liquid nitrogen cooling and were expensive, which in practice prevented their broad application. We report here recent progress in the development of broadband detection modules with HgCdTe long-wave (\(\approx 10\mu\text{m}\)) photodetectors operating without cryogenic cooling.
2. PRACTICAL REALIZATION OF HIGH-SENSITIVITY AND HIGH-SPEED PHOTODETECTORS OF LONG-WAVE RADIATION OPERATING WITHOUT CRYOGENIC COOLING

The long-wave infrared radiation detection at near-ambient temperatures have been discussed in many original papers and reviewed in the recently published monograph [7].

2.1. Device Architecture

Photodetectors are composed of multi-layer (6–20 layers) Hg$_{1-x}$Cd$_x$Te heterostructures obtained from low-temperature metal organic chemical vapor deposition epitaxy. This technology has been discussed in detail in study [8].

Figure 1 presents a construction diagram of the device, which has been simplified for reference purposes. However, the actual architecture is more complex, as the diagram does not show lesser functional layers, additional layers added to obtain a required composition and doping profile, as well as transient layers with gradations of composition and doping.

The device architecture has been optimized with the use of computer-aided simulation [9]. The thicknesses of subsequent layers, bandgap profiles, types and levels of donor and acceptor doping have been obtained from calculations. The results are as follows:

- optimal relation between absorption of exact wavelength radiation and the thermal generation rate of carriers in the absorber area,
- minimized thermal generation and recombination of carriers in contact and transient areas, and on the surface of the heterostructure,
- elimination of short-wave radiation noise by adequate choice of N$^+$ layer composition,
- good and fast collection of optically generated carriers,
- minimized parasitic impedances at the mesa structure base, wide bandgap contact areas and at the contact between the heterostructure and the metallization,
- minimized RC time constant.

The contact metallization additionally functions as a mirror reflecting low-absorption long-wave radiation back to the absorber. Buffer, absorber and contact layer thicknesses are chosen to create, along with the contact metallization, a resonant cavity, which is not particularly perfect but offers an increase in device quantum efficiency in the long-wave range [7].

Photodiode heterostructure is monolithically integrated with immersion lens which functions as an effective optical concentrator. In the hemispherical immersion lens, the optical area is increased $n^2$ times the physical area, where $n$ is the refraction index of lens material. This solution allows for a radical decrease in the thermal generation and recombination of carriers, also the noise power, which is decreased proportionally to a decline in absorber volume. A greater ($n^4$) increase is obtained for a hyperhemispherical lens. For gallium arsenide lens ($n = 3.4$), the optical area is increased by approx. 1 and 2 orders of magnitude, for hemispherical and hyperhemispherical lenses respectively.

Another advantage of immersion lenses is a decrease in electric capacity, which declines proportionately to a decrease in the absorber area. This results in a radical drop in the RC time constant. However, the use of immersion lens also has its disadvantages, such as increased manufacturing costs and, in the case of hyperhemispheric lenses, limited field of view and lowered radiation saturation threshold. Such solutions allow for a radical increase of detectivity and operating speed as compared to conventional, non-immersed detectors.

![Figure 1: Diagram section of photodiode heterostructure for approx. 10µm wavelength radiation detection in temperature 200–300 K.](image)
3. CHARACTERISTICS OF PHOTODETECTORS

Photodiode detectivity is specified on the basis of current sensitivity and dark current measurements, and the latter is used in the calculations of shot noise current, i.e., the dominating noise type in the device frequency operating band.

The RMS shot noise current can be calculated with the application of the following formula:

\[ I_n = (2 \cdot g \cdot q \cdot I \cdot B)^{1/2} \]  \hspace{1cm} (1)

where \( q \) — elementary charge, \( I \) — photodiode dark current, \( g \) — photodiode electrical gain, \( B \) — noise bandwidth.

Table 1 presents parameters of Hg\(_{1-x}\)Cd\(_x\)Te photodiode.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient Temperature</td>
<td>K</td>
<td>293</td>
</tr>
<tr>
<td>Detector Temperature</td>
<td>K</td>
<td>228</td>
</tr>
<tr>
<td>Cooler Current</td>
<td>A</td>
<td>0.7</td>
</tr>
<tr>
<td>Thermistor Resistance</td>
<td>kΩ</td>
<td>38</td>
</tr>
<tr>
<td>Detector Resistance</td>
<td>Ω</td>
<td>40</td>
</tr>
<tr>
<td>Optical area</td>
<td>mm(^2)</td>
<td>1</td>
</tr>
<tr>
<td>Reverse Bias Voltage</td>
<td>mV</td>
<td>−150</td>
</tr>
<tr>
<td>Current Responsivity ±20% (10 µm)</td>
<td>A/W</td>
<td>1.7</td>
</tr>
<tr>
<td>Current Noise Density</td>
<td>pA/Hz(^{1/2})</td>
<td>42</td>
</tr>
<tr>
<td>Detectivity ±20% (10 µm)</td>
<td>cmHz(^{1/2})/W</td>
<td>4E+09</td>
</tr>
</tbody>
</table>

3.1. Operating Speeds

Figure 2 presents the measured relation between the time constant of the photodiode response and the bias voltage. The experiment employed pulse quantum cascade lasers and detectors connected to DC transimpedance preamplifiers of high operating speed. The preamplifiers maintained a constant voltage level at the photodiode during the measurement of time constant for a given voltage setting.

Photodiodes without bias voltage are characterized by relatively long time constants. In the case of uncooled photodiodes without bias, the time constants were practically equal to the carrier lifetime of absorber material. The time constants of photodiodes without bias cooled to 230 K and 210 K were somewhat greater than for uncooled ones, but significantly lower than the carrier lifetimes of absorber material. Such relations suggest that in uncooled photodiodes without bias, signal fadeout is specified mainly by recombination of carriers in the absorber volume. In cooled photodiodes without reverse bias, the time constant is determined by both the recombination of carriers in the absorber and diffusion transport to contact areas.

![Figure 2: Relations between current responsivity and time constant of photodiode and bias voltage at 210 K.](image-url)
4. DETECTION MODULE

MIPAC detection module (Figure 3, Table 2) constitutes a modification of the OEM series detection modules developed and manufactured by Vigo System S.A. The housing features a radiation detector, one-, up to four-stage thermoelectric cooler with temperature sensor, broadband transimpedance pre-amplifier, and (in certain models) cooler controller. At the moment, the development process concentrates on the miniaturization of the detection module for its future placement inside ceramic flat pack package. The current signal from the detector is received by a broadband (up to 300 MHz) transimpedance amplifier with resultant transimpedance up to 100 kV/A. The amplifier provides an option of DC supply of reverse bias voltage to the detector (100 ÷ 600 mV), which constitutes the prerequisite for obtaining maximum signal/noise ratio in a broad frequency band. Reverse voltage causes low-frequency noise, which have, however, little impact on the total noise level of the broadband amplifier, as the bandwidth with dominating 1/f noise, i.e., 10 kHz–2 MHz, is significantly smaller than the bandwidth of the detection module.

![Figure 3: Integrated broadband detection module ≈ 10 µm.](image)

![Figure 4: Normalized responsivity spectral characteristics of Hg_{1−x}Cd_x Te photodiode (reverse bias 150 mV).](image)

Table 2: Parameters of broadband detection module ≈ 10 µm.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transimpedance @ ( R_{LOAD} = 50 \Omega )</td>
<td>V/A</td>
<td>10E + 3</td>
</tr>
<tr>
<td>Bandwidth (3dB)</td>
<td>MHz</td>
<td>0.001 – 150</td>
</tr>
<tr>
<td>Output Voltage Swing @ ( R_{LOAD} = 50 \Omega )</td>
<td>V</td>
<td>±1</td>
</tr>
<tr>
<td>Output Noise Density @ ( f_0 = 100 ) kHz</td>
<td>nV/√Hz</td>
<td>140</td>
</tr>
<tr>
<td>Average Total Output Noise Density (averaged over PA bandwidth)</td>
<td>nV/√Hz</td>
<td>816</td>
</tr>
<tr>
<td>Voltage Responsivity ±20% (10 µm)</td>
<td>V/W</td>
<td>169 000</td>
</tr>
<tr>
<td>Detectivity ±20% (10 µm) (averaged over PA bandwidth)</td>
<td>cm/√Hz/W</td>
<td>2E + 9</td>
</tr>
<tr>
<td>Thermistor Resistance</td>
<td>kΩ</td>
<td>38</td>
</tr>
<tr>
<td>TEC Voltage</td>
<td>V</td>
<td>0.7</td>
</tr>
<tr>
<td>TEC optimal Current</td>
<td>A</td>
<td>0.7</td>
</tr>
<tr>
<td>Stability of Temperature</td>
<td>K</td>
<td>0.01</td>
</tr>
</tbody>
</table>
Figure 4 presents the spectral characteristic of responsivity of photodiode cooled with two-stage thermoelectric cooler, measured in the manner specified above, at reverse voltage.

Table 2 presents parameters of detection module.

5. CONCLUSION

Broadband detection modules for long-wave infrared radiation (8–14 µm) have been developed for their application in second generation optoelectronic free-space communication links.

The analysis covered the sources of optical radiation with wavelength near 10 µm and detectors sensitive to that wavelength. The wavelength was chosen due to lesser attenuation caused by small-particle fogs and increased eye safety in comparison to the other two bands utilized in optoelectronic links, i.e., 780–850 nm and 520–1600 nm.

A carried out analysis of the available literature on the subject suggests that the best parameters of a mobile link can be obtained by the application of cascade lasers as the radiation source. Either continuous-wave or pulse kind lasers may be used.

Optical radiation receiver should be characterized by very high sensitivity. For that purpose, a Polish detector manufactured by Vigo System has been used. High sensitivity was obtained by combining a multi-layer Hg$_{1-x}$Cd$_x$Te heterostructure with an immersion lens that has been optimized for 10 µm wavelength radiation detection. To decrease the noise level the detector was equipped with a two-stage thermoelectric cooler.

The constructors believe that the use of a quantum cascade laser generating approx. 10 µm wavelength radiation and highly sensitive detector that has been optimized for that wavelength will allow for the creation of a second generation optoelectronic link, which ensures better range in adverse weather conditions as compared to the currently available options.

ACKNOWLEDGMENT

The authors would like to thank the Ministry of Science and Higher Education for their support in the field. The article was developed under research grant No. OR00008606.

REFERENCES

5. www.alpeslasers.ch.