High-speed, room-temperature CO_2 laser photodetectors

J. PIOTROWSKI

VIGO Ltd
ul. Radiowa 3, 00-908 Warszawa, Poland

Ten years have passed since the introduction of uncooled high-speed HgCdTe CO_2 laser radiation detectors have been introduced. They are cheap, rugged and easy to use. In terms of responsivity and detectivity, the performance of these detectors lies between cooled photon detectors and uncooled thermal detectors. This paper contains a brief characterization of the uncooled photodetectors presently manufactured at VIGO.

High sensitivity and fast detection of 10.6 μm CO_2 laser radiation is typically accomplished through the use of liquid-nitrogen-cooled HgCdTe quantum detectors, such as photoconductors and photodiodes. Alternatives to cryogenically cooled quantum HgCdTe devices are uncooled thermal detectors, such as pyroelectric detectors and thermistor bolometers. However, their responsivity and detectivity are low when operated at high frequencies. Still lower responsivity is provided by detectors that make use of the photon-drag effect in *p*-type germanium crystals.

Tremendous progress has been achieved since 1980, when the uncooled quantum 10.6 μm radiation detectors were first commercially available. Their performance has been highly improved by the use of newly designed Hg-Cd-Zn-Te semiconductor graded-gap structures of optimized composition and doping profiles, and the use of optical immersion and the optical resonant cavity principle.

Today a whole family of uncooled, high-speed, 10.6 μm radiation photon detectors is produced. These detectors are available as photoconductive (PC) and photoelectromagnetic (PEM) mode devices, which differ in detectivity, responsivity, response time, size of the active area, type and size of the housing.

The uncooled 10.6 μm radiation quantum detectors are characterized by a very high speed, while their responsivity and detectivity approaches or even surpasses that for commercially available, slow thermal detectors. The comparison of the frequency characteristics of currently available 10.6 μm thermal radiation detectors, liquid nitrogen-cooled photoconductors and VIGO's uncooled photodetectors is shown in Fig. 1. Let us discuss properties of these last detectors in details.

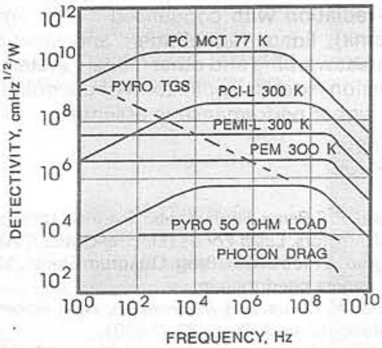

Fig. 1. Performance of uncooled detectors of CO_2 laser radiation detectors as a function of frequency.

1. Photoconductors

Photoconductive (PC) mode detectors require relatively strong electrical, constant-current biasing. The highest performance is achieved with bias power density that exceeds 0.1 W per 1 mm² area of active element. The voltage responsivity of VIGO's model R005, 1×1 mm area photoconductors for 10.6 μm radiation is over 120 mV/W. The voltage responsivity-width product is essentially constant, so the voltage responsivity for various area devices can be readily estimated as inversely proportional to the width. Detectivity is limited by Johnson noise at intermediate and high frequencies. The low frequency (1/*f*) noise typically decays above 10 kHz. Currently obtained 10.6 μm detectivity at room temperature is over 10^7 cmHz$^{1/2}$/W at frequencies 0.1–300 MHz. Please refer to Fig. 2.

The photoconductors exhibit a residual thermal response at very low frequencies (<100 Hz), which may be undesired for some applications.

2. New

Recently we have developed unique monolithic optically immersed photoconductors with highly improved performance. They achieve detectivities of $2 \cdot 10^8$ cmHz$^{1/2}$/W, the performance typical for slow thermal detectors. At the same time bias power requirements are reduced by a large factor of 7 and 50 for hemispherical and hyperhemispherical immersion, respectively in comparison with conventional non-immersed devices. See Fig. 1 where the data for the PCI-L model are shown.

3. Photoelectromagnetic detectors

Photoelectromagnetic (PEM) detectors do not require electric biasing. Rather, they utilize a magnetic field from an integral permanent magnet to separate electrons and holes created by incident photons absorbed in the semiconductor. The PEM

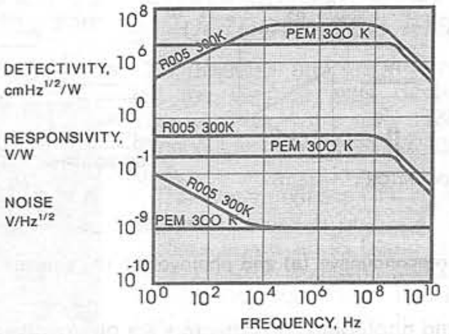

Fig. 2. Frequency characteristics of responsivity, detectivity and noise for 1×1 mm PC and PEM photodetectors.

mode device is a photovoltaic device like a *p-n* junction photodiode. An increase of PEM detectors parameters was possible by application of modern rare earth permanent magnets and cobalt steel pole pieces together with improved active element processing. The voltage responsivity of VIGO's model PEM-L, 1×1 mm PEM detector is over 50 mV/W and detectivity is over 5×10 cmHz$^{1/2}$/W. Similarly to photoconductors the responsivity-width products remains approximately constant. The low frequency 1/*f* noise does not appear, so detectivity is limited by Johnson noise and remains flat over wide frequency band, from DC to very high frequencies.

Recently, the performance of PEM detectors have been further improved by the use of optical immersion. The voltage responsivities of optically immersed series PEM-I detectors area over 0.3 V/W for 1×1 mm optical area, with detectivities exceeding $3\cdot10^7$ cmHz$^{1/2}$/W.

4. Newest: photodiffusion effect detectors

Photodiffusion effect detectors represent the new generation of ambient temperature photovoltaic detectors, based on the diffusion photovoltage in the semiconductors. They combine the advantages of photoconductors and photoelectromagnetic detectors. Requiring no electric or magnetic bias, they exhibit both high performance and speed. With no flicker noise, they can be simultaneously used to detect CW and low frequency modulated radiation. For the best performance they can be used with optical immersion. The development of these devices is ongoing and they will be available in the near future.

5. Response times

The primary reason that uncooled 10.6 μm CO_2 laser photodetectors are of interest is their ultra-fast response time. For PC devices, a time constant of 1 ns is achieved. The RC time constant, which limits the achievable speed of photodiodes and pyroelectric detectors, is unimporant here due to the low (pF range) capacitance of the thin semiconductor layer device design. Rather, carrier life-time and lead inductance seem most imporant.

In PEM and photodiffusion devices, response times can be even shorter than the carrier life-time and, in fact, is set by the carrier diffusion time through the thin HgCdTe layer. Typical response time of VIGO's PEM-L and PEMI-L model is below 0.5 ns and can be further shortened to about 0.1 ns. There is, however, some loss of performance.

6. Operating circuits

The photoconductor operating circuit shown in Fig. 3a consists of a photoconductor in series with a load resistor R and a DC bias voltage V. The output is monitored across the detector. A capacitor C is typically used to eliminate the constant voltage offset from the detector output, which is present due to the DC bias. The value of the capacitor C determines also the low frequency cut-on of the circuit.

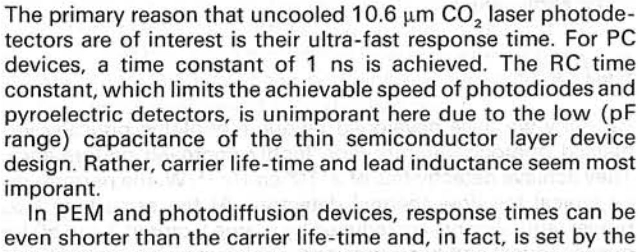

Fig. 3. Photoconductive (a) and photovoltaic (b) detector operation circuits.

PEM and photodiffusion detectors are photovoltaic devices and as such require no external bias supply. They can also be DC coupled to preamplifiers (Fig. 3b). Very low noise and wideband preamplifiers are required to achieve the potential performance of both types of detectors.

7. Damage threshold and linearity range

Average power levels of 200 W/cm on the detector surface of either PC or PEM devices represent the damage threshold limit due to heating of active elements. For pulsed radiation, the damage threshold increases to about 1 MW/cm² for sub-microsecond pulses.

However, above power levels densities of about 100 W/mm² non-linearity in output can observed due to increased carrier concentration, resulting in lower responsivity and detectivity. The voltage responsivity may decrease as a result of detector heating or due to increased carrier concentration by optical generation. The first limitation is important for CW and chopped radiation, while the second for short pulses with low repetition rates. Arbitrary selection of 20 maximum deviation from linearity as a threshold means that one must limit the maximum average power density to about 1 W. This results in an output signal for all types of room temperature photodetectors of a few tens of mV per 1 mm detector lenght. The maximum output voltage increases to about 1 V per 1 mm lenght for short, low repetition rate pluse illumination.

The optically immersed detectors are more vulnerable to laser radiation power due to concentration of radiation on active elements. The damage and linearity thresholds are reduced by a factor of about 7 and 50 for hemi- and hyperhemispherically immersed detectors, respectively, with corresponding decrease of linearity range. This poses no practical problems since the immersed detectors are used for detection of weak radiation.

8. Heterodyne detection

Uncooled HgCdTe CO_2 laser radiation detectors are especially interesting as heterodyne detectors. They lower detectivity compared to LN_2 – cooled devices can be compensated for by the higher power of the local oscillator which can be applied to the uncooled HgCdTe detector. VIGO's model PCI-L optically immersed photodetectors with detectivity exceeding $2\cdot18$ cmHz$^{1/2}$/W are as ideally suited for heterodyne detection. With these types of detectors it should be possible to obtain NEP_H as low as 10^{-19} W/Hz.

9. Conclusions

The uncooled long wavelenght semiconductor photodetectors are ideal for the detection of the pulsed and high frequency (up to over 1 GHz) modulated CO_2 laser radiation due to very short response time and perfect impedance match to fast electronics. They are also especially well suited for the heterodyne detection.

These detectors are cheap, rugged and convenient to use. Their unique features, together with a low price, should laed to the suppression thermal detectors, which are slow at comparable sensitivities and are far less sensitive at high frequencies.

Practical applications of uncooled 10.6 μm radiation detectors include detector and monitoring of CO_2 laser radiation, laser metrology, process control in industrial laser technology, medical laser applications, scientific research (for example interaction of laser radiation with condensed matter and high-temperature plasma), lidars, ragnefinders and laser communications, laser threat warning and other military systems. The use of optical immersion extends application of uncooled detectors to areas where higher performance is essential.

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