5.1. Infrared (IR) Photodetectors

Infrared photodetectors are semiconductor electro-optical devices that convert infrared radiation into an electrical signal.

$Hg_{1-x}Cd_xTe$

Known also as Mercury Cadmium Telluride (MCT), HgCdTe, (Cd,Hg)Te or MerCadTel. It is a variable ba nd gap alloy, commonly used for fabrication of photodetectors with tunable spectral response.

$InAs_{1-x}Sb_x$

$InAs_{1-x}Sb_x$ also known as Indium Arsenide Antimonide and InAsSb is another variable band gap alloy used for fabrication of photodetectors with tunable spectral response.

Physical detector area A

Active area of a detector where the incident radiation is absorbed and sensed.

Optical detector area Ao

The apparent optical area of the detector which is "seen". It is equal to physical area of the detector active element unless an optical concentrator is used. The optical detector area can be significantly magnified in detectors supplied with optical concentrators, for i.e., immersion lenses (see Optical immersion chapter).

Photoconductors (PC)

Photoconductive detectors based on the photoconductive effect. Infrared radiation generates charge carriers in the semiconductor active region decreasing its resistance. The resistance change is sensed as a current change by applying a constant voltage bias. The devices are characterized by near linear current-voltage characteristics. The electric field in photoconductors is constant across the device. It equals ratio of bias voltage and distance between contacts

$$E = V/L$$

The optimum bias voltage is specified in the final test report and depends on detector size, operating temperature and spectral response.

Photovoltaic detectors (PV, PVM)

Photovoltaic detectors (photodiodes) are semiconductor structures with one (PV) or multiple (PVM), homo- or hetero-junctions. Absorbed photons produce charge carriers that are collected at the contacts, resulting in external photocurrent. Photodiodes have complex current voltage characteristics. The devices can operate either at flicker-free zero bias or with reverse voltage. Reverse bias voltage is frequently applied to increase responsivity, differential resistance, reduce the shot noise, improve high frequency performance and increase the dynamic range. Unfortunately, at the expense of flicker noise (1/f) in most cases.

Photovoltaic detectors are more vulnerable to electrostatic discharges than photoconductors.

Photoelectromagnetic detectors (PEM)

Photovoltaic detectors are based on the photoelectromagnetic effect based on spatial separation of optically generated electrons and holes in the magnetic field. The devices do not require electrical bias and show no flicker noise (1/f). The PEM devices are typically used as fast, uncooled detectors of the long wavelength radiation.

Detector formats

Square or rectangular formats are typically used for any IR detectors. Circular geometry is sometimes used for photodiodes.

Equivalent small signal detector circuit

Electric properties of some photodetectors can be described by a small signal detector circuit which consists of photocurrent source $I_{ph}=R_i P$, detector dynamic resistance R_{sh}, capacitance C, and series resistance R_s. R_s is a parasitic resistance of the devices that reduce available photocurrent. Unfortunately, the simple model cannot accurately describe properties of long wavelength photodiodes operating at near room temperatures.

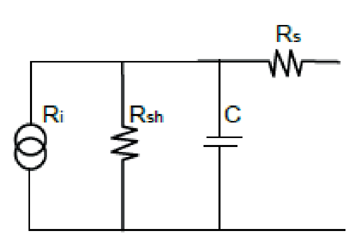


Figure 1. Equivalent small signal circuit of an IR photodetector

Photocurrent

Photocurrent is a current generated by IR radiation, which is not in thermal equilibrium with detector. For small irradiation, the photocurrent is proportional to incident radiation power P

$$I_{ph} = R_i \cdot P$$

where R_i is the current responsivity.

Current responsivity R_i

Current responsivity (A/W) is a ratio of photocurrent and power of radiation. The current responsivity is typically measured for monochromatic radiation (the spectral current responsivity) and blackbody radiation (the blackbody current responsivity). The responsivity typically remains constant for weak radiation and tends to decrease with a stronger radiation.

Current responsivity-length product $R_i \cdot L$

The current responsivity of unbiased PEM, PVM and biased (with constant electric field E) PC detectors is proportional to the reciprocal length. Therefore, the current responsivity $R_i \cdot L$ is used to compare devices of various formats.

Another normalized current responsivity, $R_i \cdot L/E$, is used to compare responsivity of photoconductive devices of various format, and operating with different electric fields.

Maximum bias voltage V_{max}

The maximum voltage that can be applied to a photoconductor or photovoltaic detector without a risk of its damage.

Dark current I_{dark}

The current that flows in a photodetector in thermal equilibrium with its surrounding.

Background generated current

The photocurrent generated by thermal radiation emitted by detector surrounding.

Noise current I_n

Root mean square noise current $I_n = \sqrt{\overline{I_n^2(t)}}$.

Noise current density i_n

$$i_n = \sqrt{\frac{dI_n^{\,2}}{df}}.$$

Flicker noise

Flicker noise or 1/f noise is a frequency dependent noise. Its power is typically proportional to 1/f.

1/f noise corner frequency f_c

Frequency, at which the low frequency noise equals the white noise (e.g., the Johnson or shot noise) so the flicker noise dominates at $f<f_c$.

Normalized detectivity D^*

The signal-to-noise ratio (SNR) at a detector output, normalized to radiant power, a detector optical area and bandwidth. D* is expressed in cm·Hz$^{1/2}$/W units.

$$D^* = \frac{I_{ph}(A_o \Delta f)^{1/2}}{I_n P} = \frac{R_i(A_o \Delta f)^{1/2}}{I_n}$$

Spectral responsivity and spectral detectivity

Dependence of responsivity and detectivity on wavelength.

Cut-on wavelength λ_{cut-on}

λ_{cuton} is a shorter wavelength at which a detector responsivity reaches 10% of the peak value.

Cut-off wavelength $\lambda_{cut-off}$

λ_{cutoff} (50%) is a longer wavelength at which a detector responsivity reaches 50% of the peak value.

Peak wavelength λ_{peak}

λ_{peak} is a wavelength of detector maximum responsivity.

Optimum wavelength

a device is optimized for. Typically it is longer than λ_{peak}.

Sheet resistance R_{sq}

It is used to compare the resistances of rectangular photoconductive, PEM and PVM devices with different aspect ratios. It equals to ratio of product of detector resistance and distance between contacts to detector width

$$R_{sq} = \frac{R \cdot L}{w}.$$

Resistance- area product $R_d \cdot A$

Area-normalized dynamic resistance, $R_d \cdot A$, of photodiodes that is used to compare photodiodes of different format in which dynamic resistance decreases proportionally to the detector active area.

Linearity range

The linearity range of detector operation is the radiation power range for which the sensitivity remains constant. It is limited by a drop in responsivity (typically specified for 10% drop).

Time constant τ

Typically, detector time response can be described by the one pole filter characteristics. Time constant is time detector takes to reach $\frac{1}{e} \approx 37\%$ of the initial signal value. The time constant is related to a 3dB high cut-off frequency f_{hi}

$$\tau = \frac{1}{2\pi f_{hi}}.$$

Time constant for one pole filter is related to 10 – 90% rise time t_r

$$t_r = 2.2 \cdot \tau.$$

Operating temperature T
The detector active element temperature.

Field of view FOV
Angular field of view is the maximum cone angle at which incoming radiation can be captured by a detector. Radiation coming from a larger angle will not reach the detector.

F-number $F/\#$
$F/\#$ is a ratio of focal length to diameter of entrance pupil. For lenses it is the ratio of focal length to diameter of lens.

Optimal operation conditions

Constant bias voltage and current readout are typically the optimum operation conditions for the best detectivity, speed of response, linearity and long term stability.

5.2. Thermoelectric coolers (TEC)

Operation of thermoelectric coolers is based on Peltier effect. Two-, three- and four-stage thermoelectric coolers are available. TEC is biased with DC current supply. The parameters of TEC depend on temperature of the hot side of cooler. It is typically specified for 300 K.

Maximum temperature difference ΔT_{max}

ΔT_{max} rated at $\dot{Q} = 0$, at other Q the ΔT should be estimated as $\Delta T = \Delta T_{max}(1 - \frac{Q}{Q_{max}})$.

Maximum heat pumping capacity Q_{max}

Q_{max} rated at $\Delta T = 0$, at other ΔT cooling capacity should be estimated as $Q = Q_{max}(1 - \frac{\Delta T}{\Delta T_{max}})$.

Maximum cooler current I_{max}

Supply current giving the highest temperature difference at the specified conditions stated in Final Test Report (supplied with each a VIGO device).

Cooler current I_{max}

Supply current used in measured detector. Stated in Final Test Report (supplied with each a VIGO device).

Maximum TEC voltage V_{max}

TEC voltage drop at ΔT_{max}.

5.3. Preamplifiers

Preamplifier is an electronic device that converts a weak electrical signal at the input into an output signal sufficient for further processing.

Transimpedance amplifier
Transimpedance amplifier (briefly called TIA) converts the current signal to the voltage. The transimpedance amplifier presents a low impedance to the photodetector and isolates it from the output. TIA low input impedance provides stable biasing conditions for the detector which helps to achieve maximum linearity and bandwidth.

Voltage swing V_{out}

The maximum and minimum voltages where preamplifier works in linear range.

GND
Point of zero potential. For standard preamplifiers there is common power supply and signal ground.

Low cut-off frequency f_{lo}

The minimum frequency at which a preamplifier gain reaches -3dB of the peak value or 0 for DC coupling devices.

High cut-off frequency f_{hi}

The maximum frequency at which a preamplifier gain reaches -3dB of the peak value.

Output noise
Noise voltage at preamplifier output.

Average output voltage noise density

$$v_n = \sqrt{\frac{\int_{f_1}^{f_2} V_{out}^2(f)df}{f_2 - f_1}}.$$

Output noise density at specific frequenc $v_n(f_0)$

Noise voltage density measured at a given frequency.

Transimpedance K_i

Output voltage to input current conversion factor (ratio)

$$K_i = \frac{V_{out}}{I_{in}}.$$

e_n – preamplifier input voltage noise density

Density of the voltage noise, given in V/sqrt(Hz), generated by the equivalent voltage noise source connected in series with the preamplifier input.

i_n – preamplifier input current noise density

Density of the current noise, given in A/sqrt(Hz), generated by the equivalent current source connected in parallel with the preamplifier input.

5.4. Detection module

Detection module integrates detector, preamplifier, thermoelectric cooler, and other components (e.g., detector biasing circuit, heat dissipation system, optics) in a common package. The operation of detection modules can be described in similar way as for detectors, by specifying their spectral and frequency characteristics of responsivity and detectivity.

Voltage responsivity R_v

The output voltage divided by optical power incident on the detector. For spectral measurements it can be expressed as

$$R_v(\lambda) = R_i(\lambda) \cdot K_i \, .$$

Frequency response

Dependence of voltage responsivity on frequency.

Voltage swing V_{out}

The maximum and minimum voltages where detection module works in linear range.

Low cut-off frequency f_{lo}

The minimum frequency at which an AC coupled module responsivity reaches -3dB of the peak value or 0 Hz for DC coupling devices.

High cut-off frequency f_{hi}

A maximum frequency at which a module responsivity reaches -3dB of the peak value.

Output noise

Noise voltage at detection module output.

Average output voltage noise density

$$v_n = \sqrt{\frac{\int_{f_1}^{f_2} V_{out}^2(f)\,dt}{f_2 - f_1}} \, .$$

Noise measurement frequency f_0

Frequency at which output voltage noise density is measured selectively.

Output noise density at specific frequency $v_n(f_0)$

Noise voltage density measured at a given frequency.

Output impedance R_{out}

Equivalent impedance exhibited by its output terminals.

Load resistance R_L

The expected resistance of the device connected to detection module's output. The parameters provided in the detection module test sheet are valid if the load resistance equals R_L. Usually R_L = 1 MOhm, for modules operating below 20 MHz, and 50 Ohm for devices operating over 20 MHz.

Output voltage offset V_{off}

Constant DC component of the output voltage, present in both with and without IR radiation.

Power supply voltage V_{sup}

Supply voltage required for correct module operation. ±20% tolerance is allowed.

Power supply current I_{sup}

Supply current consumption during correct detection module operation.

Power supply input (+) and (-)

Polarity of the power supply related to the ground. Swapping supply connectors may lead to module damage.

5.5. Thermoelectric cooler controllers

Temperature sensor inputs

Temperature sensor pins – might be connected with any polarity.

Thermoelectric cooler supply input (+) and (-)

Supply polarity for the TEC. Those pins are floating which means they are not connected to the GND.

Maximum thermoelectric cooler controller output current I_{TEC}

Maximum current that is provided by the controller.

Maximum thermoelectric cooler controller output voltage V_{TEC}

Maximum voltage that is provided by the controller.

Ripple of output current

Unwanted residual periodic variation of the DC (direct current) output of a power supply (or other device) which has been derived from an AC (alternating current) source. This ripple is due to incomplete suppression of the rectified DC waveform within power supply.

Output current of the built-in power supply
Maximum current that can be delivered by power supply to the preamplifier, usually +/-100mA.

Series resistance of the connecting cable
Material parameter - resistance of the supply cable. It depends on cable length.

Settling time of the set detector temperature
The time taken by the cooling system to reach appropriate temperature of the detector.

Maximum voltage across thermoelectric cooler element
Maximum voltage for thermoelectric cooler supplying.

5.6. Technical informations for VIGO products

Standard TEC parameters

Parameter	Cooling		
	-2TE	-3TE	-4TE
T_{det} [K]	~230	~210	~195
V_{max} [V]	1.3	3.6	8.3
I_{max} [A]	1.2	0.45	0.5
Q_{max} [W]	0.36	0.27	0.28
ΔT_{max} [K]	92	114	125

Temperature sensor

The built-in thermistor serves as a sensor of the detector operation temperature. TE-cooled detectors are equipped with thermistor type **NCP03XM222E05RL** as a standard.

NCP03XM222E05RL thermistor characteristics

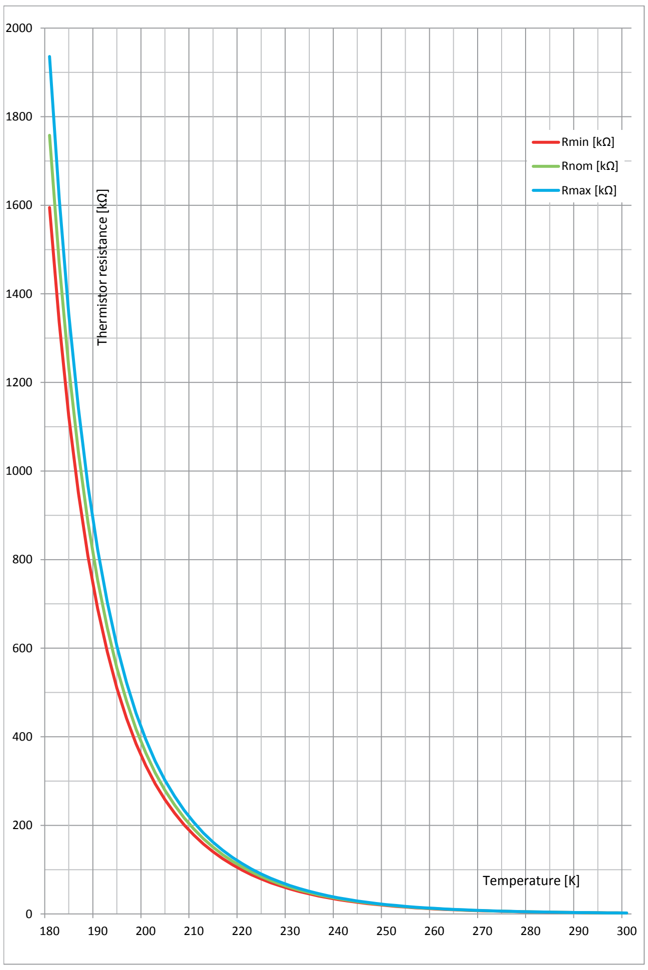
The electricity applied between terminals of thermistors should be under the maximum power dissipation at 25^oC $(100mW)$ in order not to destroy the thermosensor. For the measurement of resistance, the power should not exceed the relation between the resistance and the temperature:

$$R_T = R_{T0}exp\left(\beta\frac{T_0 - T}{T \cdot T_0}\right)$$

$$R_{T0} = 2.2k\Omega \pm 3\% \text{ at } T_0 = 298K\ .$$

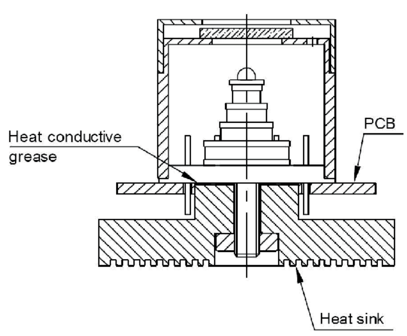
Resistance vs. temperature for NCP03XM222E05RL thermistor

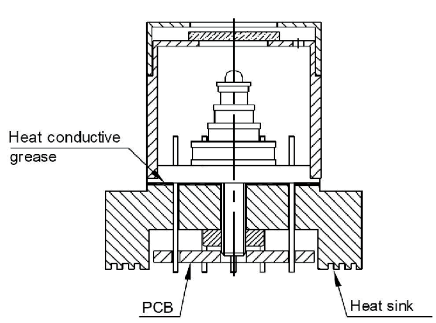
T [K]	T [°C]	R_{min} [kΩ]	R_{nom} [kΩ]	R_{max} [kΩ]
180	-93	1594.97	1757.95	1935.84
182	-91	1336.02	1469.90	1615.75
184	-89	1124.16	1234.66	1354.81
186	-87	950.46	1042.11	1141.58
188	-85	807.57	883.99	966.78
190	-83	689.57	753.62	822.88
192	-81	591.68	645.64	703.89
194	-79	510.07	555.75	604.98
196	-77	441.68	480.54	522.34
198	-75	384.05	417.25	452.91
200	-73	335.23	363.71	394.26
202	-71	293.65	318.17	344.43
204	-69	258.05	279.23	301.88
206	-67	227.41	245.76	265.36
208	-65	200.91	216.85	233.85
210	-63	177.89	191.77	206.55
212	-61	157.81	169.92	182.79
214	-59	140.22	150.80	162.03
216	-57	124.76	134.02	143.83
218	-55	111.14	119.25	127.83
220	-53	99.10	106.21	113.72
222	-51	88.44	94.67	101.25
224	-49	78.98	84.44	90.21
226	-47	70.57	75.37	80.42
228	-45	63.09	67.30	71.73
230	-43	56.42	60.12	64.01
232	-41	50.49	53.74	57.15
234	-39	45.19	48.05	51.04
236	-37	40.47	42.98	45.61
238	-35	36.26	38.47	40.77
240	-33	32.51	34.45	36.47
242	-31	29.16	30.87	32.64
244	-29	26.18	27.68	29.24
246	-27	23.51	24.84	26.21
248	-25	21.14	22.30	23.51
250	-23	19.02	20.05	21.11
252	-21	17.13	18.04	18.98
254	-19	15.45	16.25	17.07
256	-17	13.95	14.65	15.38
258	-15	12.61	13.23	13.87
260	-13	11.41	11.96	12.53
262	-11	10.34	10.83	11.33
264	-9	9.38	9.82	10.26
266	-7	8.52	8.91	9.31
268	-5	7.75	8.10	8.45
270	-3	7.07	7.37	7.69
272	-1	6.45	6.72	7.00
274	1	5.89	6.13	6.38
276	3	5.38	5.60	5.83
278	5	4.93	5.13	5.32
280	7	4.52	4.69	4.87
282	9	4.15	4.30	4.46
284	11	3.81	3.95	4.09
286	13	3.50	3.63	3.75
288	15	3.22	3.33	3.45
290	17	2.96	3.06	3.17
292	19	2.73	2.82	2.91
294	21	2.51	2.59	2.68
296	23	2.32	2.39	2.46
298	25	2.13	2.20	2.27



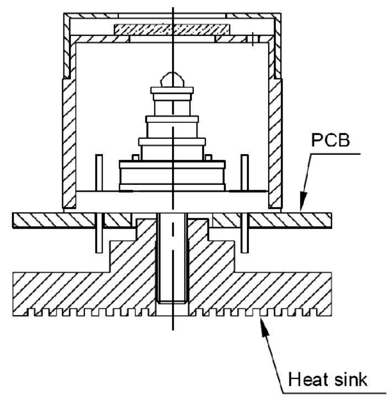
Heat sinking

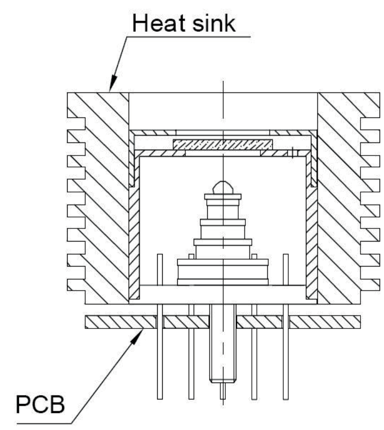
Suitable heat sinking is necessary to dissipate heat generated by the Peltier cooler or excessive optical irradiation. Since heat is almost 100% dissipated at the base of the detector housing, it must be firmly attached to the heat sink (Figures a and b).





Heat sinking via the mounting screw or via the detector housing cylindrical walls is not sufficient (Figures c and d).





A thin layer of heat conductive epoxy or silicone grease should be applied to improve thermal contact between detector housing and heat sink.

A heat sink thermal resistance of $\sim 2\frac{K}{W}$ is typically recommended for the most one-, two- and three-stage Peltier coolers. For four-stage TE cooler, thermal resistance $\sim 1\frac{K}{W}$ is recommended.

Optical immersion

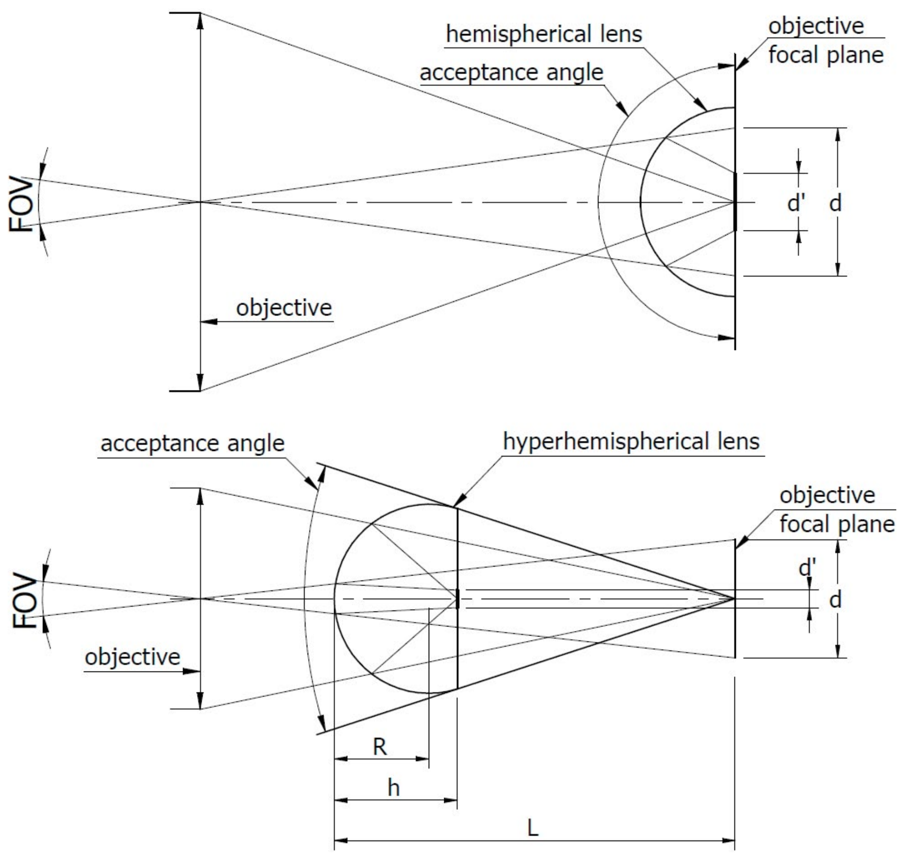
Optical immersion is achieved by using high refractive index microlenses in order to improve performance of the devices but may limit acceptance angle.

Optical immersion is a monolithic integration of a detector element with hyperhemispherical microlens (basic configuration) that makes optical linear size of detector 11 times larger compared to its physical size. This results an improvement of D* by one order of magnitude and electric capacitance by a factor of two orders of magnitude less compared to a conventional detector of the same optical area.

Function and properties of hemispherical and hyperhemispherical lenses are illustrated in Figure and in Table below.

Immersed detectors parameters

Parameter	Symbol	Hemisphere		Hyperhemisphere	
		Theory	GaAs	Theory	GaAs
Distance	L	R	R	R(n+1)	4.3R
Linear size ratio	$\frac{d}{d'}$	n	3.3	n^2	10.9
Detectivity ratio	$\frac{D^*_{imm}}{D^*_{non-imm}}$	n	3.3	n^2	10.9
Aceptance angle	ϕ	180	180	$2arcsin\left(\frac{1}{n}\right)$	35
F-number for objective lens	F/#	each	each	$\geq \sqrt{\left(\frac{n}{2}\right)^2 - \frac{1}{4}}$	≥1.57



“Function and properties of hemispherical and hyperhemispherical lense.”

n – refractive index of lens material (~3.3 for GaAs used by VIGO)
d – optical (apparent) detector size
d' – physical detector size
R – lens radius
L – lens face to objective focal plane distance
$h = R + \frac{R}{n}$ lens thickness

The values in the Table show the relative change of a given parameter comparing to a non-immersed detector of the same optical size. Detectors with custom acceptance angles are available upon request.