Desing of a long wave infrared (LWIR) bolometric detection structure

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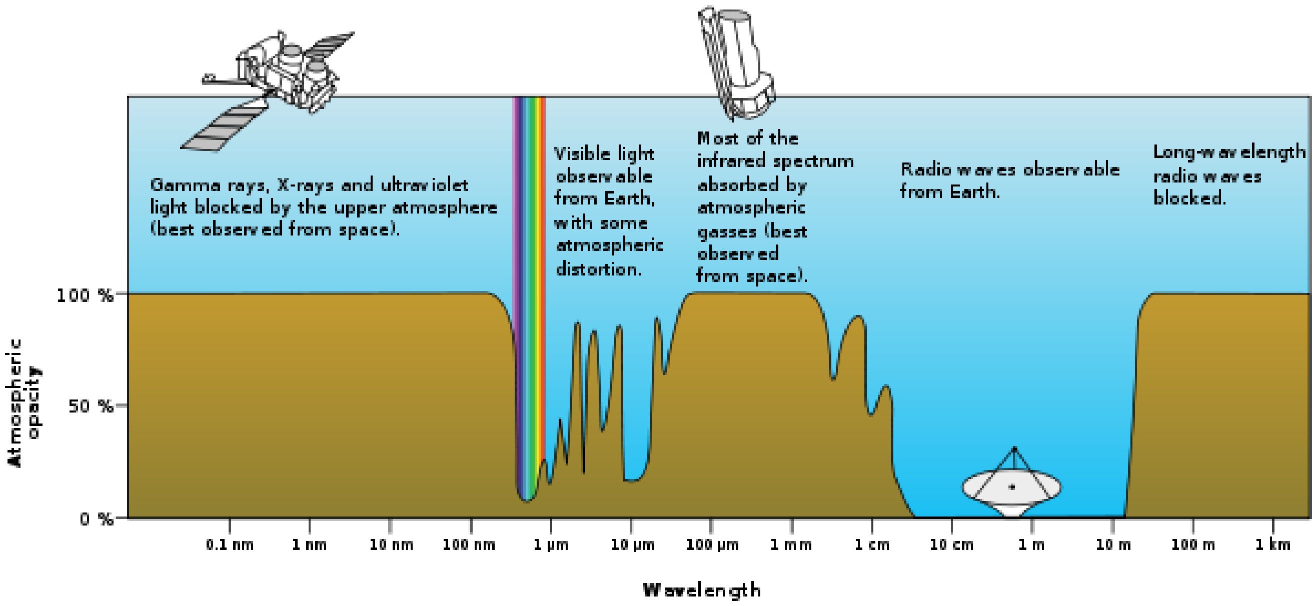
1. Introduction to Long-Wave Infra-Red (LWIR) bolometers

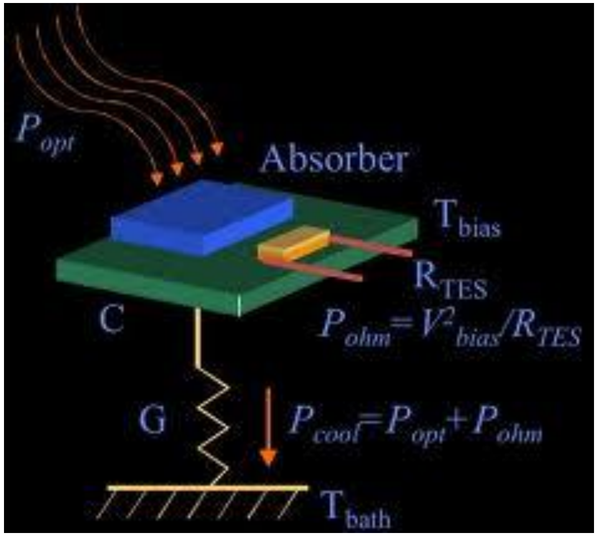
- Infrared imaging bolometers have found great utility in ground-base and space imaging applications.
- Bolometers measure incident energy by observing a temperature change when a material absorbs photons.
- Most recent developments of imaging bolometers have focused on the long-wave IR (LWIR) range from 8 μm to 13 μm because the atmosphere is fairly transparent in this range, which also encompasses the peak emission from warm objects on Earth.
- For faint or cold astronomical targets, cryogenically cooled LWIR and sub-millimeter arrays have been developed and have been adapted for use in space, as is the case of the Planck and Herschel telescopes.



1. Introduction to Long-Wave Infra-Red (LWIR) bolometers

(Bolometer fundamentals)

- In its simplest form, a bolometer consists of an energy-absorbing material connected to a thermomether with a weak thermal connection to a constant temperature heat sink.
- Incident radiant energy heats the absorber, raising its temperature which is measured by the bolometer.



Schematic drawing of a superconducting bolometer

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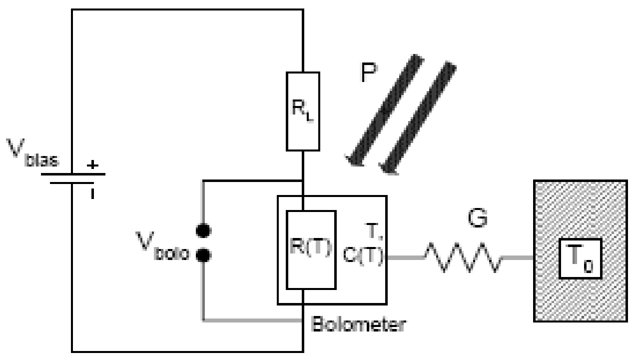
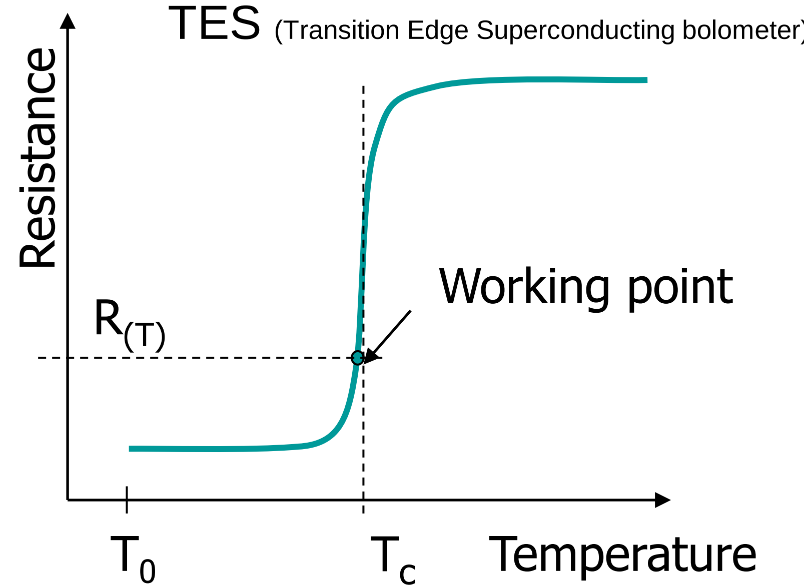


Schematic electrical and thermal circuit diagram for a superconducting bolometer. The bolometer with heat capacity C(T) and resistance R(T) is connected to a thermal bath maintained at constant temperature T_0 through a weak link of thermal conductance G, which includes any radiative and convective components. The incident power absorbed, P, changes the temperature and thus the resistance of the bolometer.
The change of the bolometer resistance is detected by measuring the change in the applied bias voltage across the bolometer.
In current bias condition, $R_L >> R(T)$



A superconducting bolometer utilizes the tremendous change in resistance that occurs in the transition of certain metals and semiconductors from their normal to the superconducting state.
Voltage-biased, the electrical power is given by
$P_{bias}=V_{bias} / R_L$
$P_{total}=P+P_{bias}$
T_c remains constant.

1. Introduction to Long-Wave Infra-Red (LWIR) bolometers

(Bolometer fundamentals)

- A wide range of materials can be used as the energy absorber to control the operating spectral range.
- With low G, one can improve the bolometerr performance, by using low emissivity materials on the detector backside in a thin support, and connecting elements with low thermal conductivity.
- The speed of response of a bolometer is governed by the bolometer time constant τ.
- The maximum bolometrer detectivity is limited by random fluctuations in the radiant power exchange between the detector and scene.
- The Noise Equivalent Power (NEP) is the incident power on the detector generating a signal output equal to the rms noise output. Or is the power absorbed that produces a S/N of unity at the detector output (units: $WHz^{-1/2}$).

$$\Delta T = \int \frac{\varepsilon(\lambda)P(\lambda)}{\sqrt{G^2+\omega^2 C^2_{(T)}}} d\lambda$$

The rise in the detector element temperature, where ε is the emissivity of the absorber, P is the power incident on the absorber element, and ω is the frequency of the incident power envelope.

$$\tau = \frac{C(T)}{G}$$

For bolometers, the time constant is generaly of the order of a few miliseconds, which is much slower than the photon detectors.

$$D^* = \sqrt{\frac{\varepsilon}{8\kappa_B\sigma(T^5+T_s^5)}}$$

The detectivity of a bolometer, where κ_B is Boltzmann´s constant, σ is the Stefan-Boltzmann constant, T is the detector temperature, and Ts is the scene temperature.

$$NEP^2_{Total} = NEP^2_{Bolo} + NEP^2_{Bgr}$$

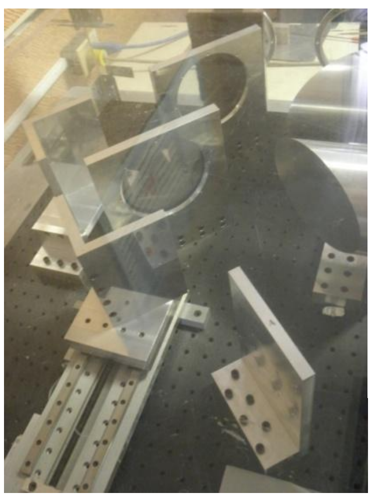
$$D^* = \frac{1}{NEP_{Total}}$$

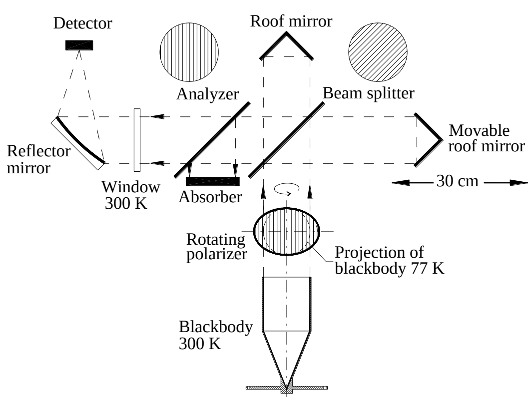
The detectivity of a bolometer, can also be dertermined by the inverse of the NEP_{Total}

1. Introduction to Long-Wave Infra-Red (LWIR) bolometers

(Bolometer fundamentals)

- Observations of warm targets such as the Earth and Planets can easily be accomplished with detectors cooled at sub-ambient temperatures.
- Astrophysical observation must be done with detectors cooled down to few kelvins or less (few hundreds of mK).
- Nowadays compact closed-cicle cooling systems and bolometer-array fabrication are available for these trends, reaching temperatures from few hundreds of milikelvin up to room temperatures.
- All bolometers need to be calibrated in a laboratory before being installed into a telescope.





Fourier Transform Spectrometer (FTS) at the INAOE´s facilities.

4-He Cryo-cooler, with a current closed cycle (from 4 K to 300 K). Nearly future from (0.3 K to 300 K). At the INAOE´s facilities.

4-He Cryostat, with a closed cycle (from 10 K to 300 K), at the INAOE´s facilities.

1. Introduction to Long-Wave Infra-Red (LWIR) bolometers

(Bolometer fundamentals)

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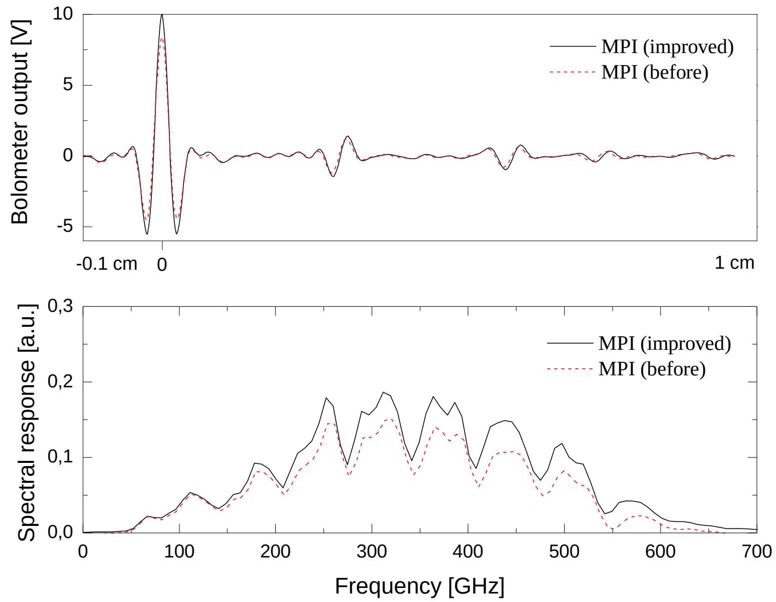


Interferograms and spectral response of a bolometer

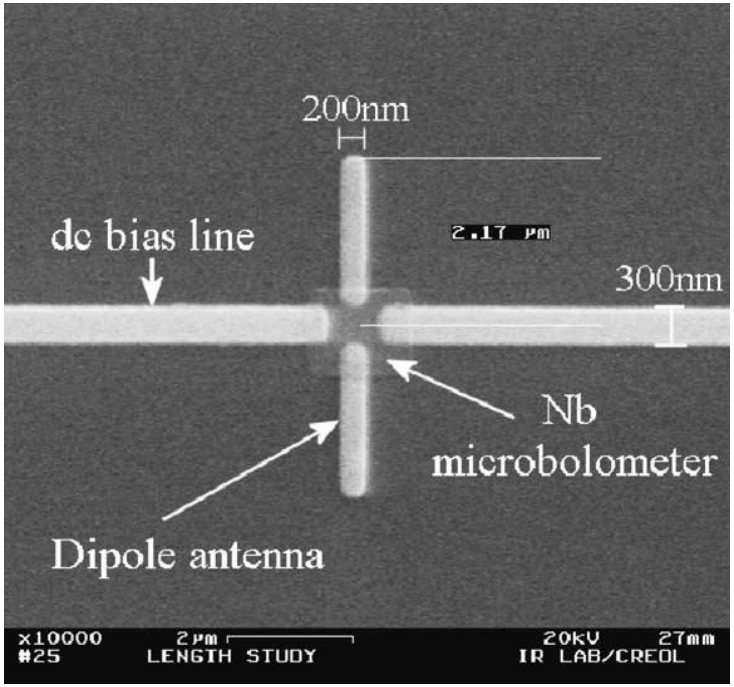
A. Colin, Cryogenics 47, (2007), 530-533

2. Antenna-coupled infrared microbolometers

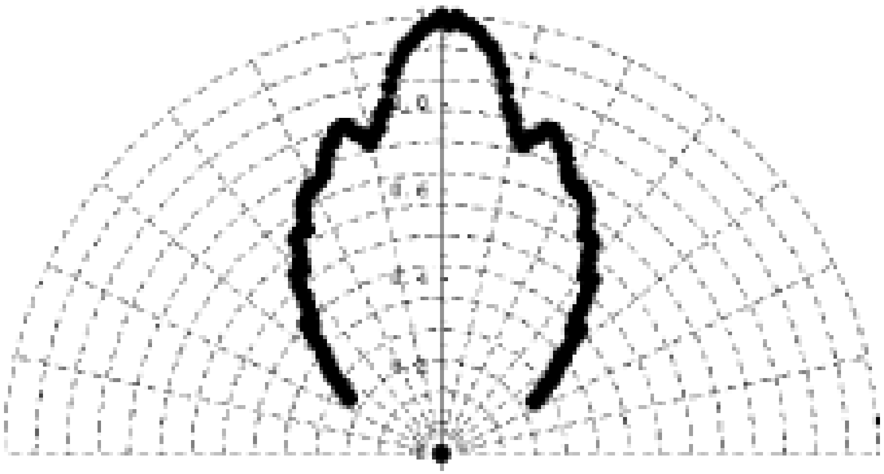
- In the 1980´s started the use of the term “microbolometer”, which describes bolometric detectors smaller than wavelength.
- By reducing the size of a bolometer, will increase its sensitivity because a lower amount of energy is needed to increase its temperature. Therefore it will have a smaller time constant.
- A disadvantage of reducing the size of a bolometer is that less energy gets collected since bolometers use their physical size to collect radiation.
- A way to increase the collection area of a small bolometer is to couple an antenna designed to resonate at the desired wavelength, in this way we can have fast detectors without sacrificing collection area.

2. Antenna-coupled infrared microbolometers

- Uncooled antenna coupled microbolometers are fast adetectors with good sensitivity, directivity and can be polarization and wavelength selective.



Dipole-coupled microbolometer



Radiation pattern of a dipole-coupled microbolometer

Figures taken from:
F.J. González, Infrared Phys Tehcnol 46 (2005), 418

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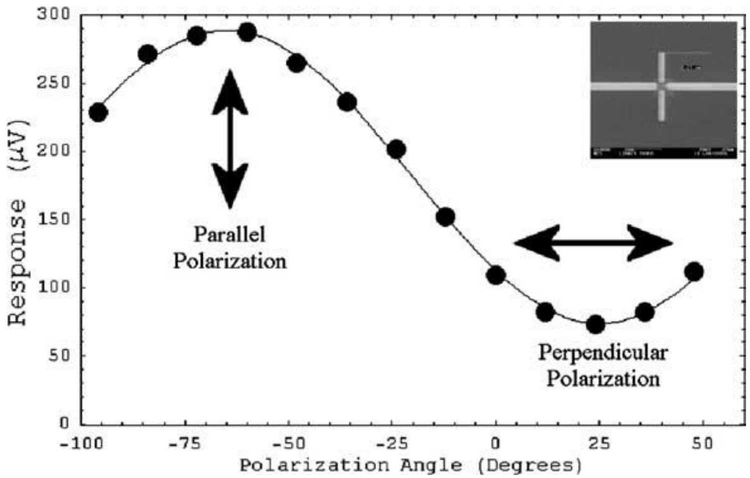
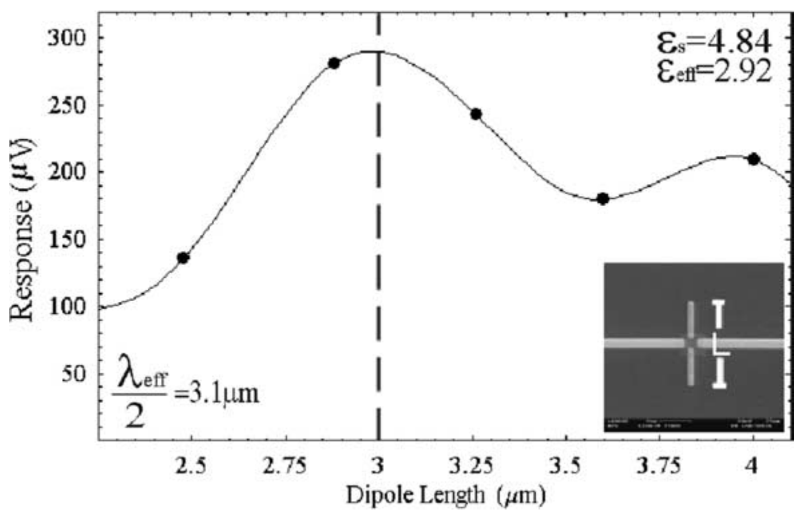


Polarization dependence for a dipole-coupled microbolometer

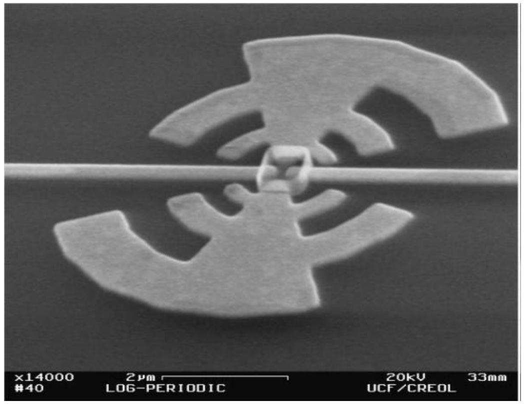


Response of a microstrip dipole as a function of its length.

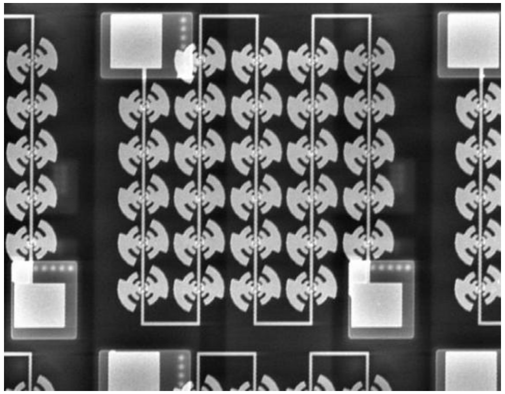
Figures taken from:
F.J. González, Infrared Phys Tehcnol 46 (2005), 418

2. Antenna-coupled infrared microbolometers

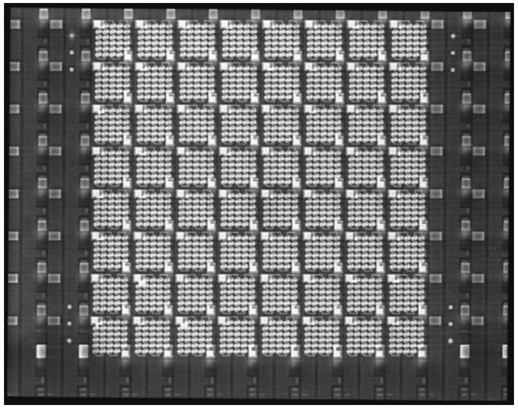
- Uncooled antenna coupled microbolometers have typically collection areas in the order of 10 x 10 μm2 per pixel.
- A two dimesional array of NxN elements serially connected may increase the signal-to-noise ratio of a single detector by a factor of N.
- The miniaturization of this elements composed by arrays of antenna-coupled bolometers makes feasible its integration into commercial Read Out Integrated Circuits (ROICs).



Log-periodic antenna coupled to a Nb microbolometer



Antenna-coupled pixel



8x8 Pixel array of antenna-coupled infrared detectors integrated into a commercial ROIC

Pictures taken from
F.J. González, Proc. SPIE, 5406, 2004

3. Magnesium diboride (MgB_2) superconducting thin-film (T_c = 39 K)

- MgB2 is a simply binary intermetallic compound that has hexagonal structure with transition temperature of 39 K.

  W. N. Kang et al, Science 292, 1521 (2001)

- Bolometers cooled down to temperatures of 39 K are being developed for use in future planetary missions.

  B. Lakew et al, NASA TRS GSFC.JA.00388.2012

- The future exploration missions to Uranus, Neptune and their respective icy moons require high resolution investigation, hence bolometers fabricated with MgB2 are being promising for this respect.

  B. Lakew , Proc. SPIE ,7003, 2008

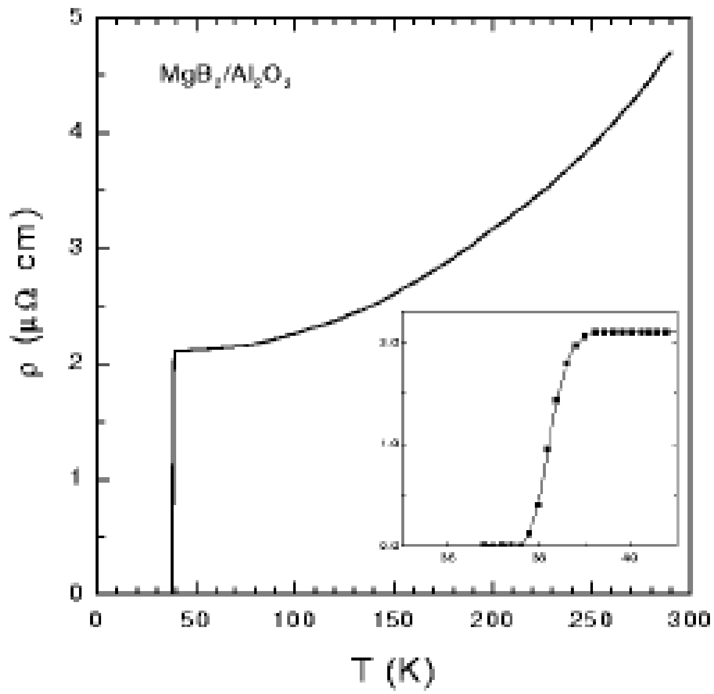
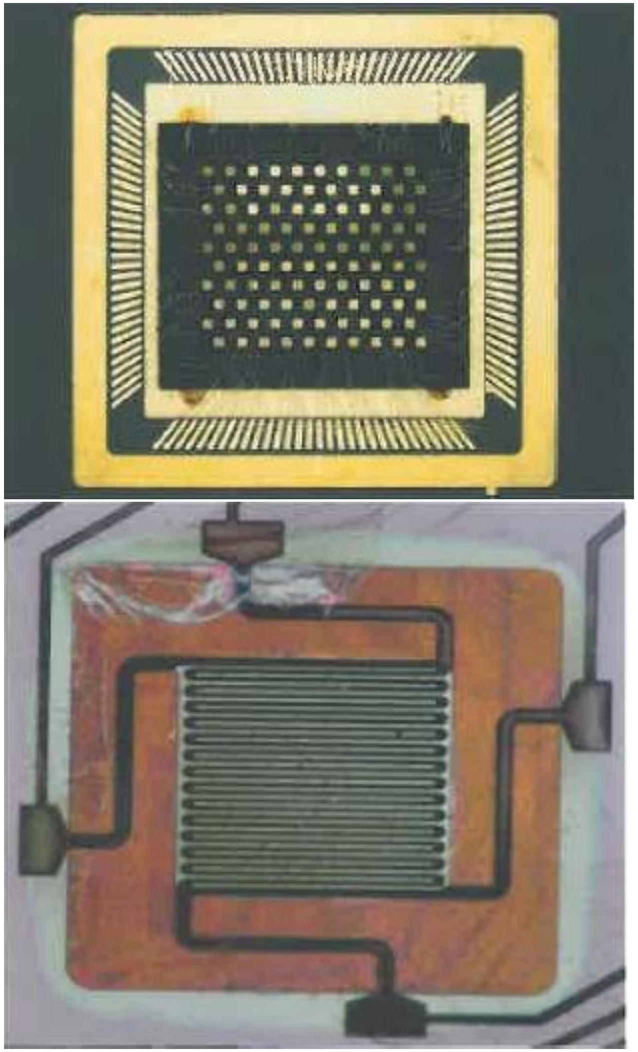


Figure taken from
W. N. Kang et al, Science 292, 1521 (2001)

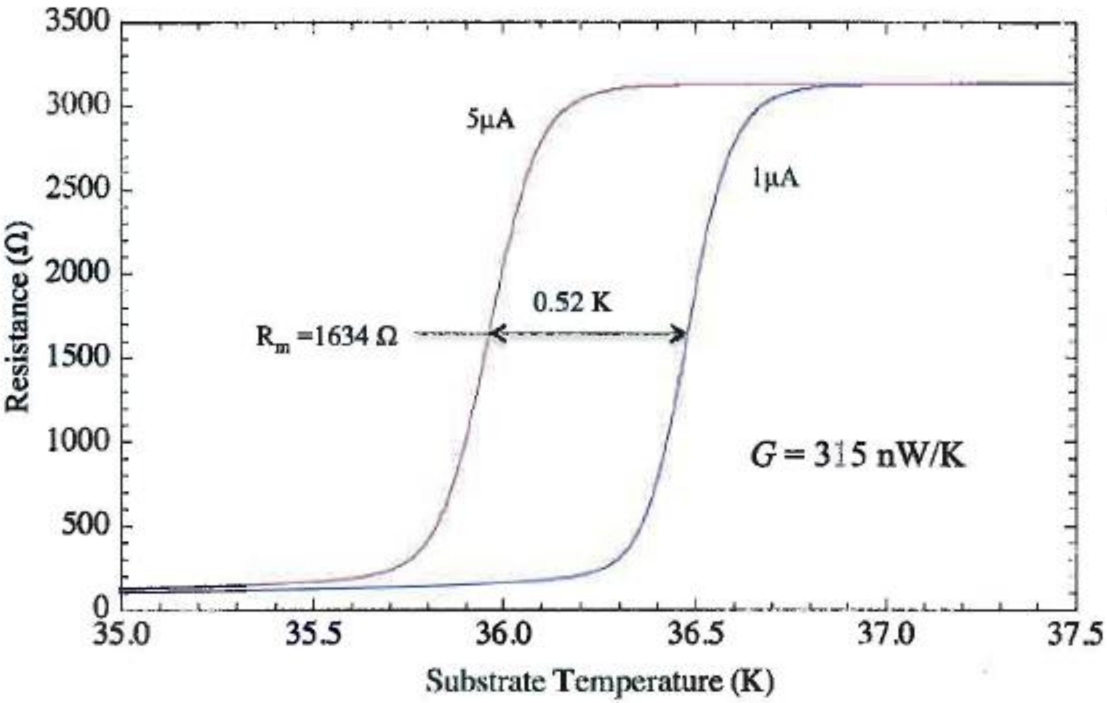
MgB2 superconducting thin films with a transition temperature of 39 Kelvin

Angel Colin 5/09/2012

3. Magnesium diboride (MgB_2) superconducting thin-film (Tc = 39 K)



10 x 10 MgB2 bolometer array (up), and MgB2 bolometer pixel (250 x 250 μm2 (down).

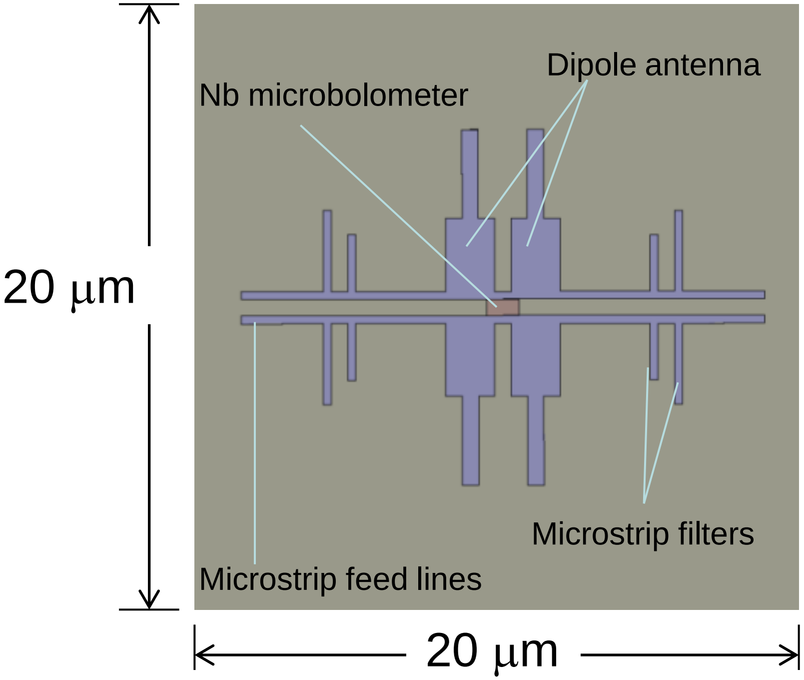


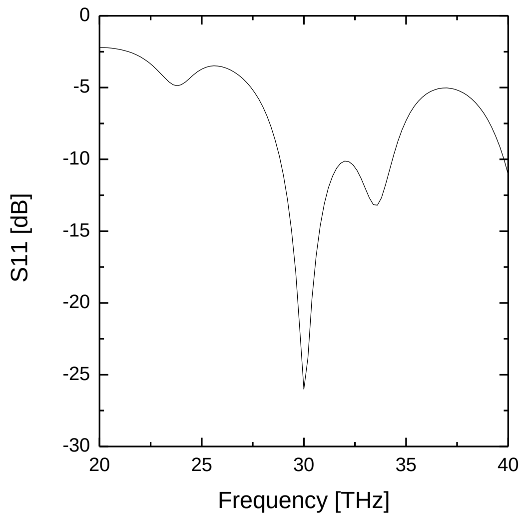
MgB2 superconducting thin films with a transition temperature of 36 Kelvin

Pictures taken from
B. Lakew et al, NASA TRS GSFC.JA.00388.2012

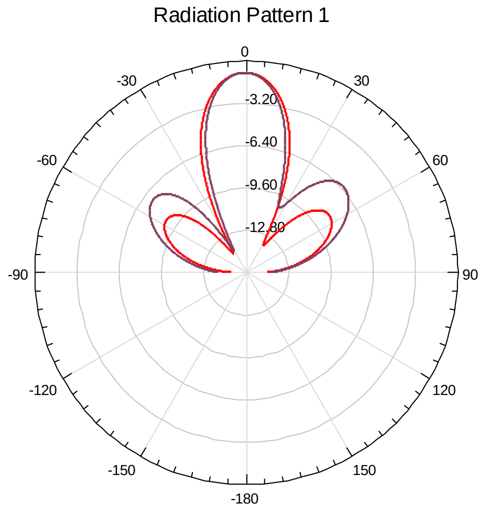
4. Design of a LWIR bolometric detection structure

- The proposed design consists in a double dipole antenna-coupled to Nb microbolometer of 1 x 0.5 μm2 and (Tc = 9.2 K).
- The antenna structure is supported by a silicon nitride membrane (Si_3N_4) suspended on a perforated Si substrate.
- We use microstrip filters to define the frequency band over which the bolometer is sensitive (30 THz = 10 μm).
- This antenna has a nearly symmetrical beam.





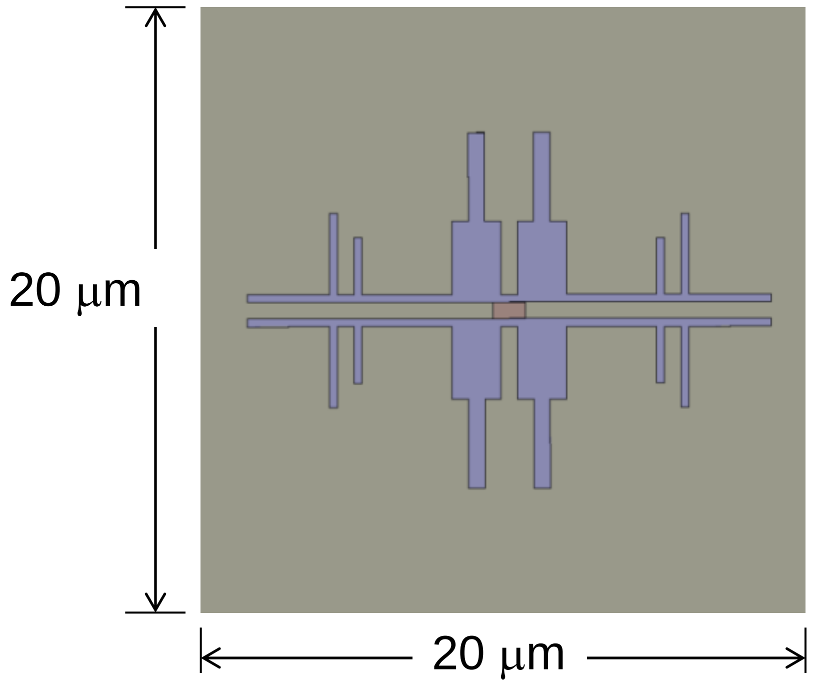
Return loss better than -10 dB

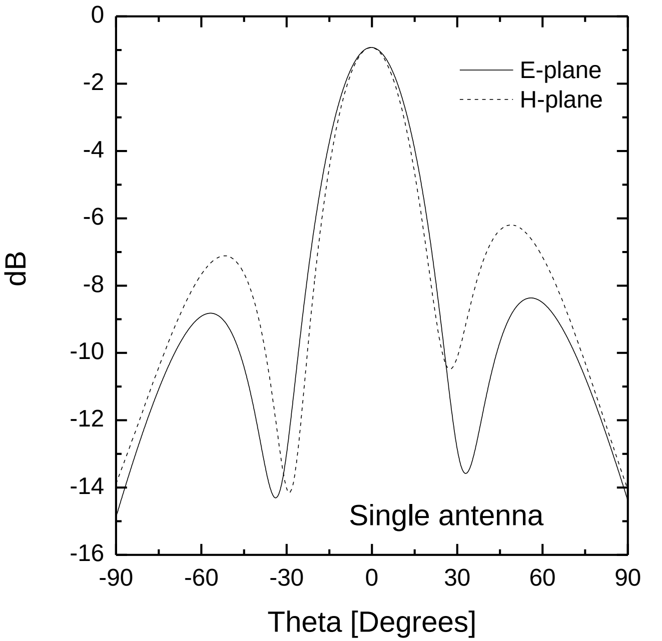


Radiation patern at 30 THz
E-plane (red)
H-plane (black)

4. Design of a LWIR bolometric detection structure

• The proposed design operates at Tc = 9.2 K for astronomical application, while operating at 300 K may be used for civilian applications.





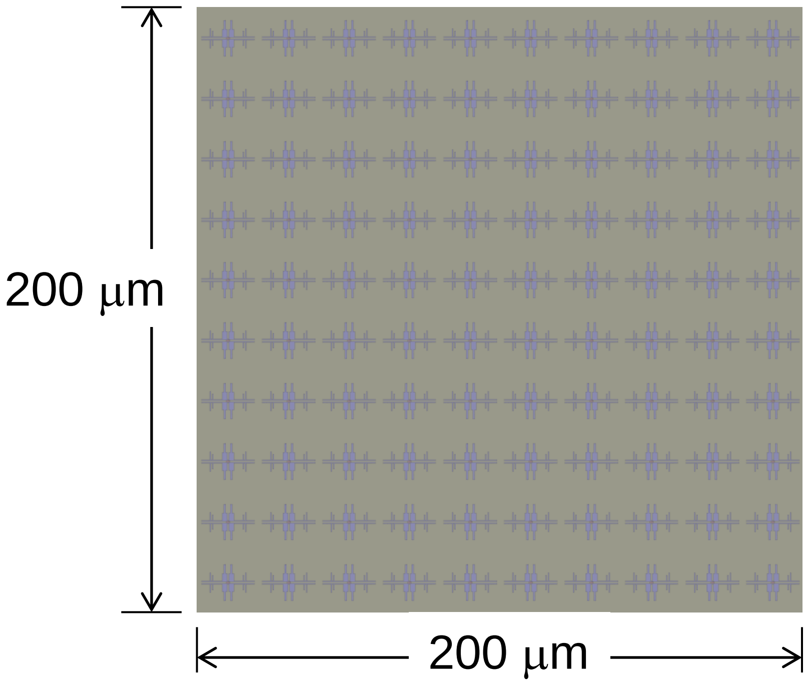
Radiation patern at 30 THz

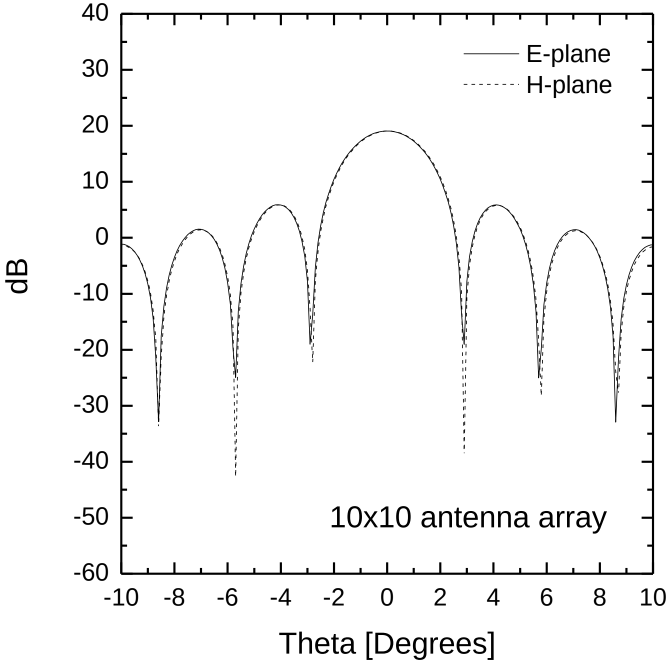
Single antenna

HPBW = 12.7° aprox.

4. Design of a LWIR bolometric detection structure

• By increasing the number of antenna-coupled microbolometers in a N x N elements array , the HPBW and can be reduced approximately by a factor of N, while the antenna's gain can be increased by a factor of 3 approximately.





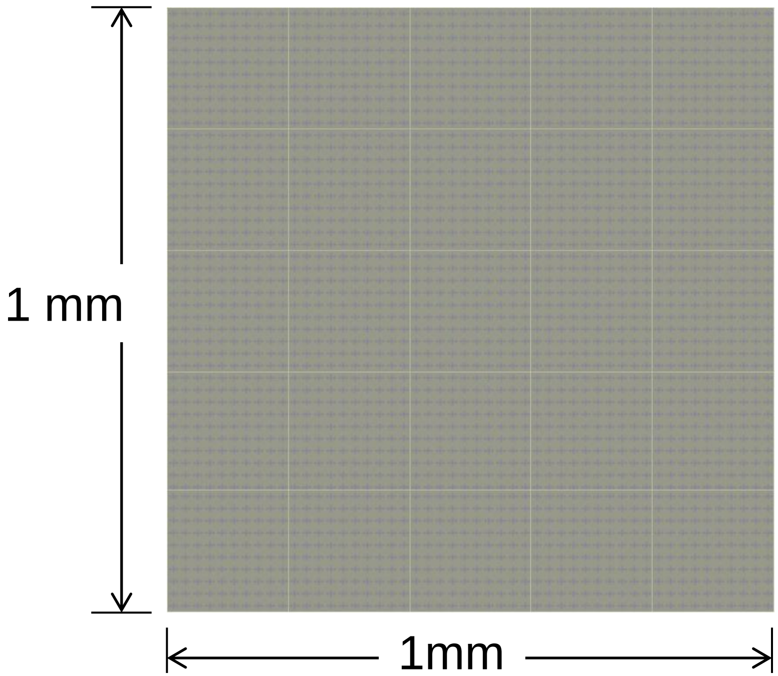
Radiation patern at 30 THz

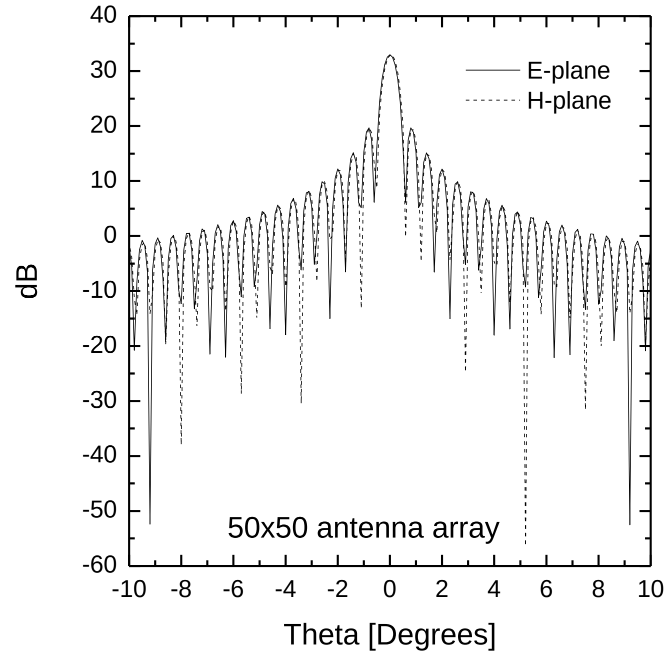
10x10 antenna's array

HPBW = 1.2° aprox.

4. Design of a LWIR bolometric detection structure

• For our purposes an array of 50 x 50 elements of antennas is enough to cover a pixel area of 1 mm2.





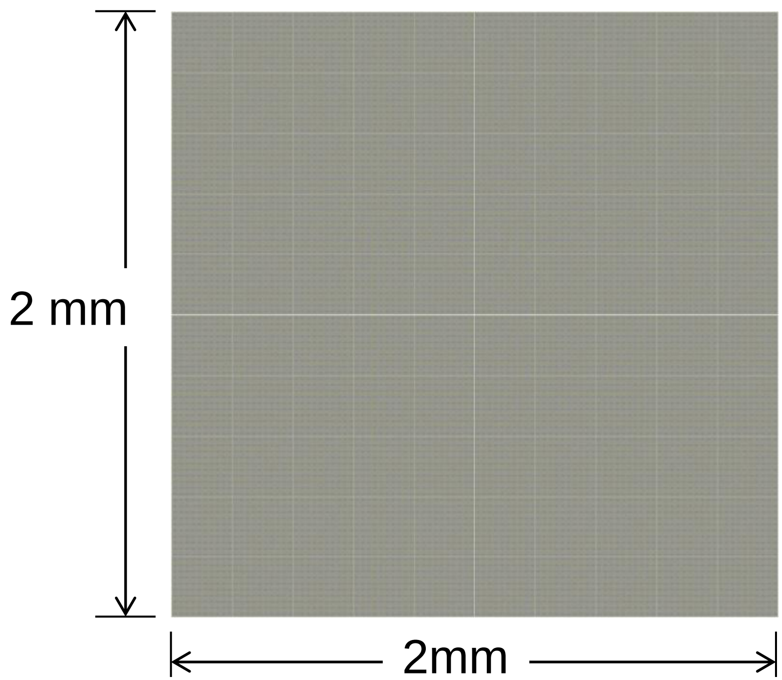
Radiation patern at 30 THz

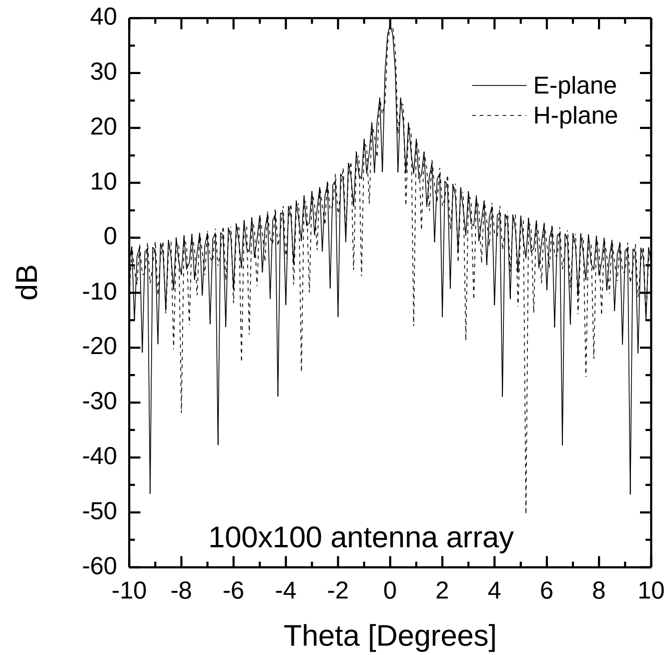
50x50 antenna's array

HPBW = 0.3° aprox.

4. Design of a LWIR bolometric detection structure

• An array with 100 x 100 elements is better than the previous one but increases the pixel size by a factor of two.





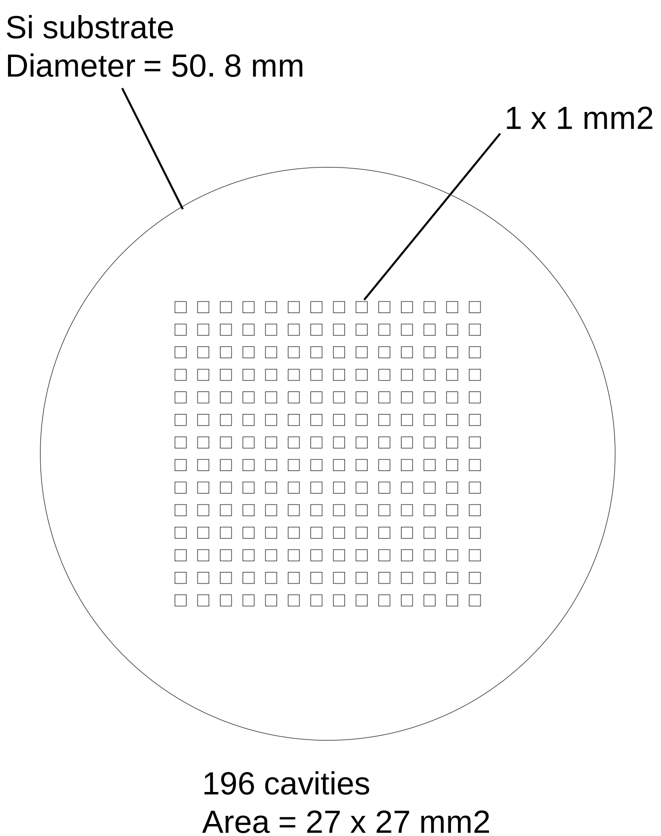
Radiation patern at 30 THz

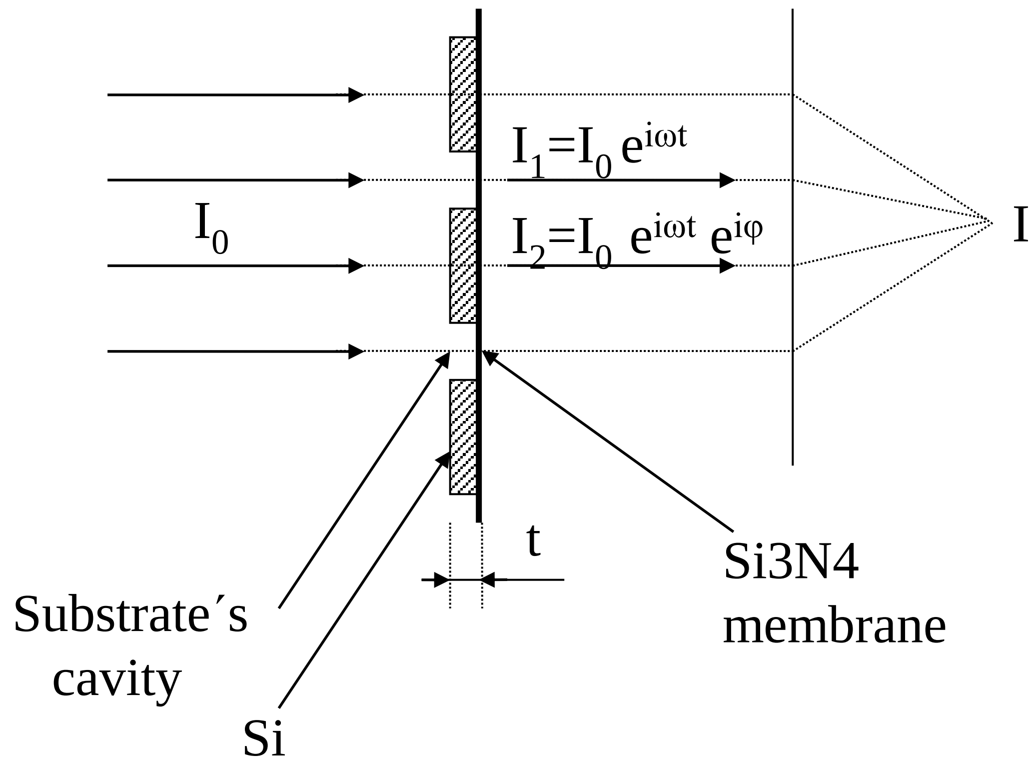
100x100 antenna's array

HPBW = 0.1° aprox.

4. Design of a LWIR bolometric detection structure

• An array of 196 cavities. Each cavity supports a silicon-nitride membrane.

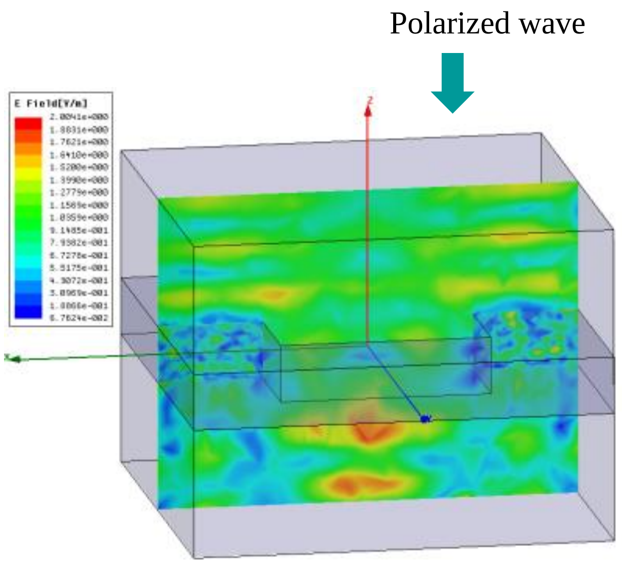


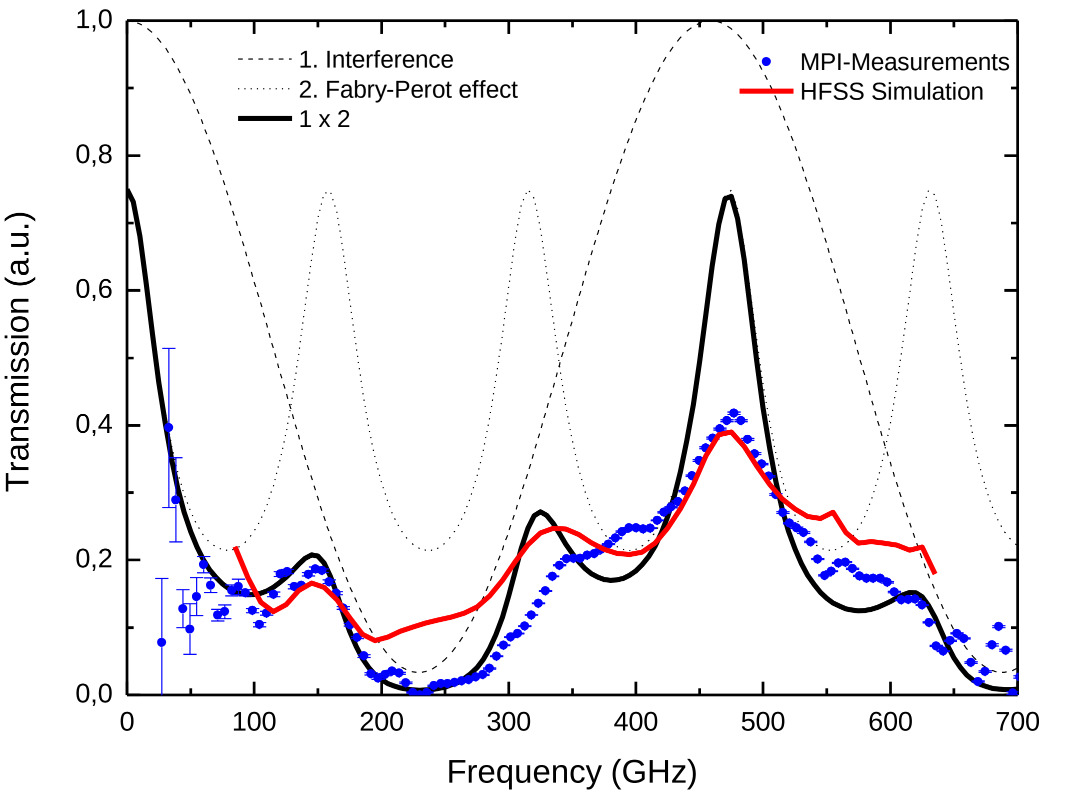


A. Colin, Journal of Optics (2012) (Submitted)

4. Design of a LWIR bolometric detection structure

• Transmission measurments compared with analytical and simulation results of a Si_3N_4 membrane.





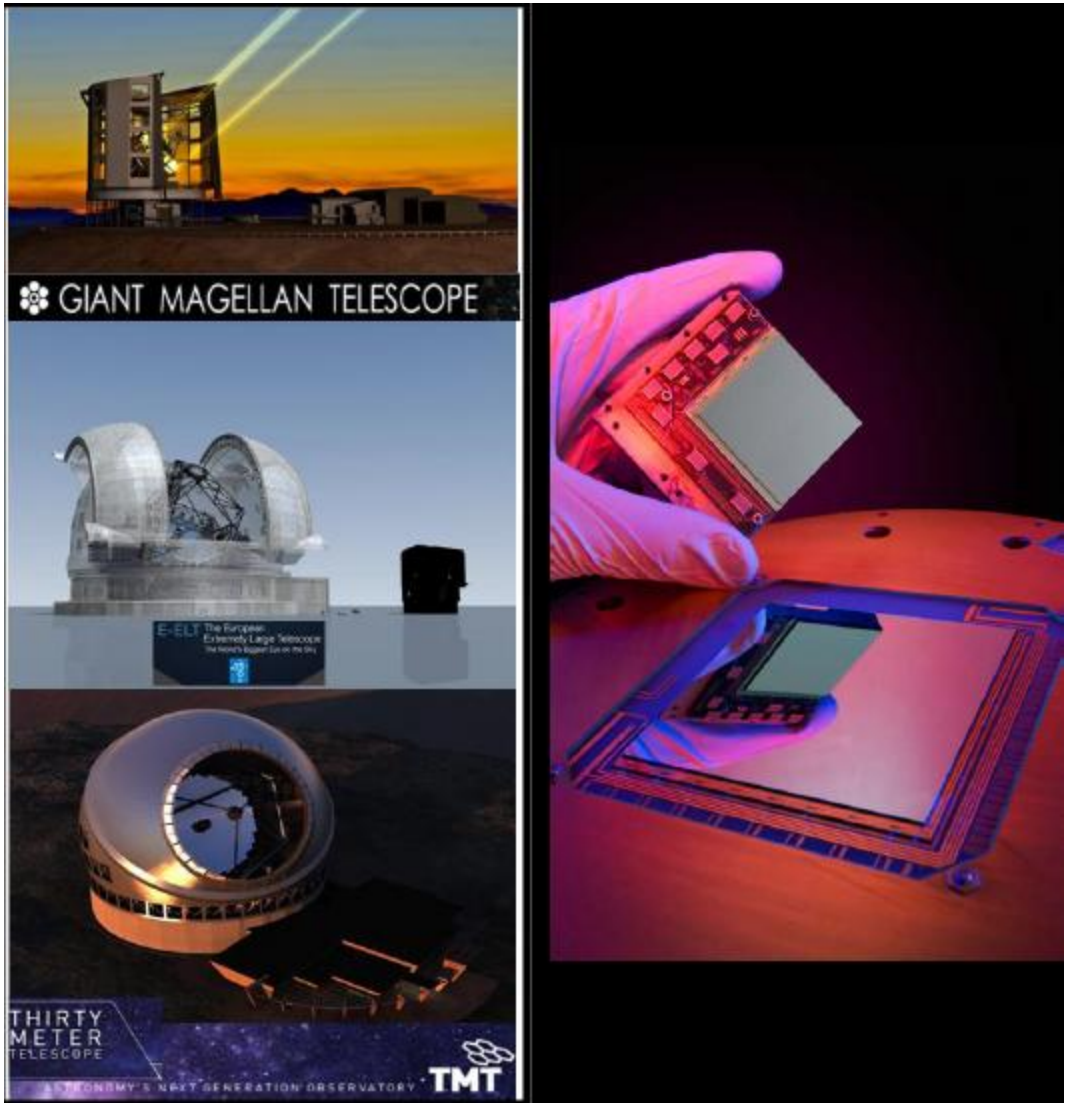
A. Colin, Journal of Optics (2012) (Submitted)

4. Design of a LWIR bolometric detection structure

•Summary of the figures of merit found in the literature.

Antenna-Coupled Micro-bolometer [Tc]	**Application**	**Supercond. material**	**NEP** [$WHz^{-1/2}$]	**D*** [$cmHz^{1/2}W^{-1}$]	τ [s]	**Antenna HPBW** [Degrees]
300 K (normal metal)	Civilian markets	Nb	1.16×10^{-4}	8.6×10^{3}	130 ns	12.8
90 K	Civilian markets	YBaCuO	1.5×10^{-12}	6.6×10^{11}	30 - 150 ns	-
39 K	Planetary missions	MgB2	2.56×10^{-14}	6.4×10^{10}	5.2 ms	-
9.2 K	Deep Astronomy	Nb	1.4×10^{-12}	7.5×10^{10}	100 -150 ns	0.3

5. Read Out Integrated Circuits (ROIC's) and Focal Plane Arrays (FPA)



4k × 4k MCT/Si Prototype Focal Planes

White Paper Prepared by:
Raytheon Vision Systems
75 Coromar Drive
Goleta, CA 93117

5. Read Out Integrated Circuits (ROIC's) and Focal Plane Arrays (FPA)

• Raytheon Vision Systems develops high performance Read-Out Integrated Circuits (ROIC's) for select customers in the aerospace, industrial, and medical industries. Our mixed-signal designs incorporate all of the digital features needed to command the chip and process the pixel data for imaging systems.

• Capabilities:

Large format ROICs (up to 64 Megapixel)
High-frame rate staring arrays (>10kHz)
On-chip A/D and real-time image processing
Ultra-low noise readout

•Applications:

Military/Defense/Security
Space
Astronomy
Medical
Industrial
Commercial

•Related Publications:

- Recent Focal Plane Arrays for Astronomy and Remote Sensing Applications at RVS, SPIE 2010.
- High Performance Large Format Impurity Band Conductor Focal Plane Arrays for Astronomy Applications, SPIE 2010.
- 1024 X 1024 Si:As IBC Detector Arrays for Mid-IR Astronomy, SPIE 2006.

5. Read Out Integrated Circuits (ROIC's) and Focal Plane Arrays (FPA)

Standard Readout Functions

	ISC9803	ISC0002	ISC9901	ISC0402*	ISC0403	ISC0905
Array Size	640 x 512	640 x 512	640 x 512	640 x 512	640 x 512	640 x 512
Input Circuit	Direct Injection	CTIA	Direct Injection	Direct Injection	Direct Injection	Direct Injection
Integration Type	Snapshot mode	Snapshot mode	Snapshot mode	Snapshot mode	Snapshot mode	Snapshot mode
Integration Time	Adjustable integration time > 9.6 μs	Adjustable integration time > 5.4 μs	Adjustable integration time > 100 μs	Adjustable integration time > 0.5 μs	Adjustable integration time > 0.5 μs	Adjustable integration time > 100 μs
Integration Modes	Integrate-While-Read Integrate-Then-Read	Integrate-While-Read Integrate-Then-Read	Integrate-Then-Read	Integrate-While-Read Integrate-Then-Read Non-destructive Read	Integrate-While-Read Integrate-Then-Read	Integrate-While-Read Integrate-Then-Read
Gain Adjustment	2 bit (x1, x1.3, x2, x4)	1 bit (x1, x27)	2 bit (x1, x1.3, x2, x4)	N/A	N/A	N/A
Operational Modes	"Hands-off" default User configurable	"Hands-off" default User configurable	"Hands-off" default User configurable	"Hands-off" default User configurable	"Hands-off" default User configurable	"Hands-off" default User configurable
Windowing	Dynamic windowing Window size-position	Dynamic windowing Window size-position	Dynamic windowing Window size-position	Dynamic windowing Window size-position	Dynamic windowing Window size-position	Dynamic windowing Window size-position
Readout Modes	Invert [row] Revert [column] Inverse [row-column] Interlaced mode	Invert [row] Revert [column] Inverse [row-column] Interlaced mode	Invert [row] Revert [column] Inverse [row-column] Interlaced mode	Invert [row] Revert [column] Inverse [row-column]	Invert [row] Revert [column] Inverse [row-column]	Invert [row] Revert [column] Inverse [row-column]
Number of Outputs	Selectable 1, 2, or 4 Reference output	Selectable 1, 2, or 4 Reference output	Selectable 1, 2, or 4 Reference output	Selectable 1, 2, or 4 Reference output	Selectable 1, 2, or 4 Reference output	Selectable 4 or 8 Reference output
Detector Application	p-on-n InSb or QWIP	p-on-n InGaAs or MCT	p-on-n InSb or QWIP	p-on-n InSb, InGaAs, MCT, or QWIP	p-on-n InSb	p-on-n or n-on-p InSb, InGaAs, MCT, SLS

FLIR
SANTA BARBARA
Commercial Systems
FLIR Systems, Inc.
70 Castilian Drive.
Goleta, CA 93117
USA

6. Conclusions

- The presented design of an antenna-coupled microbolometer can be implemented into the new technologies based in ROICs

- Antenna-coupled microbolometers can also be used for millimetric and submillimetric ranges by simply geometrically scalling the antenna and filters.

- Most of the new developments for thermal detectors include planar antenas.

- The use of planar antennas combined with microstrip filters provides frequency selection for operating LWIR microbolometers.

- The design presented here is aimed to be included in FPAs due to their high reliability, lightweight, low power consumption, radiation hardness and cost efficiency, with a broad range of astrophysical applications.

¡Thank you!