Design of Infrared Wavelength-Selective Microbolometers using Planar Multimode Detectors

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ABSTRACT

Multimode microbolometers for wavelength-selective infrared detection have been designed using a Genetic Algorithm and an electromagnetic model of the planar antenna. Wavelength selectivity can be varied by changing the distance to a tuning mirror, or by changing only lithographically drawn parameters, with bandwidth narrower than Fabry-Perot microbolometers. The design of a three color system covering the 7-14 micron band is presented.

Keywords: microbolometer, wavelength selectivity, infrared detector, focal plane array

1. INTRODUCTION

Multi-channel, wavelength selective infrared detection has been extensively studied for numerous applications, e.g., night vision, thermal imaging, nondestructive detection, remote sensing, and missile guidance and defense. For cooled detectors, narrow bandwidth wavelength selectivity has been achieved using quantum-well infrared photo-detectors (QWIPs) [1], quantum-dot infrared photo-detectors (QDIPs) [2], or infrared band-pass filters in front of microbolometers [3]. For conventional un-cooled micromachined infrared microbolometers integrating wavelength selectivity into the detector itself is somewhat harder to achieve. The most common approach to both enhance coupling and produce some degree of wavelength selectivity is the use of a Fabry-Perot structure consisting of a microbolometer placed in front of a mirror [4]-[6]. However, a simple Fabry-Perot microbolometer produces a fairly broad spectral response.

It is possible to replace the normal uniform absorbing sheet used in IR microbolometers with true microbolometers (i.e., bolometers that are much smaller than the wavelength) combined with an antenna. Here we present a design (Figure 1) that can substantially improve the wavelength selectivity of an uncooled microbolometer. This planar multimode antenna has been extensively studied for infrared and millimeter-wave detection by Rutledge and Schwarz [7]. The electromagnetic behavior of this array can be analyzed using a modification of waveguide post-mount analysis [7, 8]. The power absorption efficiency is wavelength dependent, and is a function of the array period a, the capacitive gap width g, the inductive post width w, the distance to the mirror d, and the sheet resistance of the bolometer layer R_s (Figure 1 (b)). According to Rutledge and Schwarz, there is an upper limit on the spacing that can exist between rows or columns of the periodic structure imposed by the possibility that the structure may act as a grating. To avoid this, we restrict our designs so that the array period a is less than the shortest wavelength considered in a given design.

2. ARRAY BEHAVIOR

There are many combinations of array dimensions, a, g, w, d, and R_s , that can produce a detector with high absorption at a designated wavelength. Figure 2 shows calculated array responses using the modified post-mount model [7, 8] combined with an ABCD matrix analysis [9]. The behavior of the array approaches that of a simple Fabry-Perot microbolometer when g and w approach a, and R_s approaches 377 Ω (Figure 2, dotted line); in this case the array bandwidth is as wide as the Fabry-Perot microbolometer (shown for reference in Figure 2, dashed line). Other designs can produce much narrower bandwidth (e.g., Figure 2, solid line), narrow enough to construct multiple channels within

the 7 to 14 μ m infrared band. The diversity of the solutions is an advantage of this multimode detector, allowing a search for desired characteristics.



Figure. 1:(a) Focal plane arrays using planar multimode detectors; (b) configuration of a pixel consisting of a periodic grid of wide metal sheets connected by narrow resistive strips with detectors on them [7]; (c) equivalent circuit model of the planar multimode detector [7].



Figure. 2: Designs of multimode detectors with unity absorption at a center wavelength of 10 μm, but with widely varying bandwidths. The bandwidth can be as wide as the Fabry-Perot microbolometer (dashed line), and narrow enough to construct multiple channels within the 7 to 14 μm infrared band (solid line). All specific design geometries are given in Table 1.

	Fabry-Perot	Planar Multimode Detectors		
	dashed	dotted	dash-dot	solid
а	NA	7.00 µm	5.33 µm	6.90 µm
g	NA	5.00 µm	1.00 µm	0.20 µm
w	NA	4.50 μm	0.96 µm	3.0 µm
d	2.50 μm	2.50 μm	3.61 µm	3.29 µm
$R_{\rm s}$	377 Ω	377 Ω	30 Ω	53.49 Ω

Table. 1: Specific designs yielding the response curves given in Figure. 2.

3. TUNING OF WAVELENGTH SELECTIVITY BY MECHANICAL ACTUATION

Using the array discussed above we first consider tuning of wavelength selectivity by changing the distance to the mirror *d*, which could be performed using a mechanical actuation (Figure 3). Here, we set three wavelengths, 8, 10, and 12 μ m, as the designated wavelengths that should be reached using the tuning mechanism. Figure 4 shows the contour plots of the power absorption efficiency versus wavelength and distance to the mirror *d* for a fixed dimension array. The design used in this figure is the same as that which produced the solid line in the Figure 2. As seen from the solid line in Figure 2, this design has good power absorption efficiency at 10 μ m when *d* is equal to about 3 μ m. As shown in figure 4, we can achieve high absorption at 12 μ m wavelength by increasing *d* to about 5.7 μ m. However, this shift results in a fairly broad spectral response. In addition, peak spectral absorption can be shifted to 8 μ m wavelength by setting *d*=0.2 μ m, but the coupling efficiency very poor. Consequently, tuning for this set of array dimensions by changing the distance *d* is not an attractive solution.



Figure. 3: Tunable wavelength selective focal plane arrays using planar multimode detectors by mechanical actuation.



Distance to the mirror $d(\mu m)$

Figure. 4: The contour plots of the power absorption efficiencies versus wavelength and the distance to the mirror *d* for a fixed array dimension with *a*, *g*, *w*, and R_s are 6.90 µm, 0.20 µm, 3.0 µm, and 53.49Ω, respectively. For such an array the absorption at high wavelength results in high absorption at shorter wavelengths, while the power absorption efficiency at short wavelength is too low.

It is possible, however, to find a set of array dimensions that does allow tunable wavelength selective coupling using only the distance to the mirror as a tuning variable. The Genetic Algorithm (GA) was adopted as an optimization scheme [10]. Here we optimize for a fixed dimension array (a, g, w, and R_s all fixed) but with three different distances from the mirroreachs elected to maximize absorption at three designated wavelengths, 8, 10, and 12 µm, using the cost definition in Equation 1. This cost definition makes each channel as narrow as possible to identify the incident wavelengths, and as high as possible at the designated wavelength to absorb more power. Figure 5 shows the optimized results. By changing only d from 1.65 µm to 5.10 µm, each channel has high absorption at its own designated wavelength and its bandwidth is reasonably narrow. Here, the optimized a, g, w, and R_s for tuning by the distance d are are 5.07 µm, 1.42 µm, 0.74 µm and 21.04 Ω , respectively.

if
$$C_1 > 0$$
 and $C_2 > 0$ and $C_3 > 0$
 $cost = \frac{1}{C_1 + C_2 + C_3}$ eq.1
 $C_1 = effi._{8\mu m} (8\mu m) - \max(effi._{10\mu m} (8\mu m), effi._{12\mu m} (8\mu m))$
 $C_2 = effi._{10\mu m} (10\mu m) - \max(effi._{8\mu m} (10\mu m), effi._{12\mu m} (10\mu m))$
 $C_3 = effi._{12\mu m} (12\mu m) - \max(effi._{8\mu m} (12\mu m), effi._{10\mu m} (12\mu m))$
otherwise

 $cost = \infty$

effi._{designated λ}(λ) : absorbed power efficiencies at λ designed for the designated λ .



Figure. 5: Successful accomplishment of wavelength selectivity tuning by changing only the distance to the mirror *d*, which can be achieved by simple actuation, on the planar multimode detectors with fixed *a*, *g*, *w*, and R_s : *a*=5.07 µm, *g*=1.42 µm, *w*=0.74 µm, and R_s =21.04Ω.

4. DESIGN FOR WAVELENGTH SELECTIVITY

Next we design three separate pixels, each with peak spectral response at a different wavelgnth, each located at their optimum distance from the tuning mirror (Figure 6). This could be used to produce a three color array, but would require a process using different sacrificial layer thicknesses for each of the pixels. For each pixel, our design goal is to maintain strong absorption at a specified wavelength within the $7\sim14 \mu m$ infrared band while minimizing the absorption bandwidth of the antenna about that wavelength. To locate narrow bandwidth array designs that couple strongly at a desired wavelength, we have used a cost definition for the GA that seeks at least 99% power absorption at a specified wavelength, while minimizing the power absorbed at other wavelengths. This is accomplished by minimizing the area under the absorption curve, as given by Equation 2:

if Power Absorption Efficiency
$$\left|_{designated \lambda} > 0.99\right|$$

 $cost = \int_{7\mu m}^{14\mu m}$ Power Absorption Efficiency $(\lambda) d\lambda$ eq.2
otherwise
 $cost = \infty$

The narrowest bandwidth curve in Figure 2 (solid line) is the result found by the GA using the cost function given by equation 2 for a center wavelength of 10 μ m. Similarly, the narrowest bandwidth curves can be designed for center wavelength of 8 and 12 μ m.



Figure. 6: Pixels located in parallel for wavelength selectivity which does not require mechanical actuation. Here the distances between the microbolometer and the mirror for three pixels are different, $d_1 \neq d_2 \neq d_3$.



Figure. 7: Three color design found by optimizing three different multimode pixel geometries shown at Figure 6, each with different lithographically drawn dimensions a, g, w, d, and R_s . Power absorption efficiencies are almost unity at the designated wavelengths while each pixel would have enough wavelength selectivity to clearly distinguish three colors. All specific design geometries are given in Table 2.

	dashed	solid	dotted
а	6.90 µm	6.90 µm	6.90 µm
g	0.18 µm	0.20 µm	0.18 µm
w	4.77 μm	3.00 µm	1.5 μm
d	3.00 µm	3.29 µm	3.31 µm
R _s	55.18 Ω	53.49 Ω	62.94 Ω

Table. 2: Specific designs yielding the response curves given in Figure. 7.

Figure 7 illustrates the optimized results for three pixels. All power absorption efficiencies are high at the desired wavelengths and narrow enough to distinguish infrede colors indepednently. Specific design geometries for Figure 7 are given in Table 2. Here the most dominant factor for shifting of an absorption wavelength is a post width w. Notice that a, g, d, and R_s are similar for all three designs.

From a fabrication perspective it would be very useful if it were possible to produce three pixels with desired spectral response but all using an identical value for d (the distance between the bolometer and the mirror). The only method available for changing wavelength selectivity in a conventional Fabry-Perot microbolometer is by changing d. Hence, to construct a multi-wavelength focal plane array (i.e., one in which different pixels have different wavelength selectivities) would require a fabrication process with different sacrificial layer thicknesses under different pixels in the array. This could result in a complex process and high cost. Here we study only designs with identical distance d between the multimode array pixels and the mirror, changing the wavelength selectivity of each pixel by changing only the lithographically drawn parameters: the array period a, the gap width g, and the post width w (Figure 8). To further simplify the fabrication of such a multi-color focal plane array, we have also constrained the bolometer sheet resistance R_s to be constant for all pixels, allowing the use of a single bolometric material. To find a three color design the cost function for the GA is modified as follows (Equation 3). We require that three different multimode pixels, each with different dimensions a, g, and w, be found such that each pixel absorbs at least 99% at its designated center wavelength, while total out of band power absorption be minimized; this leads to a eleven parameter design search, a_1 , g_1 , w_1 , a_2 , g_2 , w_2 , a_3 , g_3 , w_3 , d, and R_s . Here we selected the center wavelengths of 8, 10 and 12 microns. The corresponding cost function for the GA is given by

if
$$effi_{\cdot_{8\mu m}}(8\mu m) > 0.99$$
 and $effi_{\cdot_{10\mu m}}(10\mu m) > 0.99$ and $effi_{\cdot_{12\mu m}}(12\mu m) > 0.99$
 $cost = \int_{7\mu m}^{14\mu m} \{effi_{\cdot_{8\mu m}}(\lambda) + effi_{\cdot_{10\mu m}}(\lambda) + effi_{\cdot_{12\mu m}}(\lambda)\}d\lambda$ eq. 3
otherwise
 $cost = \infty$

where $eff_{i,\text{desired }\lambda}(\lambda)$ is the power absorption efficiency at the desired center wavelength.



Figure. 8: Pixels located in parallel for wavelength selectivity which does not require mechanical tuning. Here the distances between the microbolometer and the mirror for three pixels are different, $d_1=d_2=d_3$.

Figure 9 shows the GA optimized results. The GA selected an array to mirror distance d of 3.14 µm, bolometer sheet resistance of 56.6 Ω /square, the same array period a and gap width g for all three different wavelength selective pixels (6.8 µm and 0.20 µm, respectively), with the only difference being in the post width w: the 8 micron pixel would have a post width of 4.57 µm, the 10 micron pixel would have a post width of 2.80 µm, and the 12 micron pixel would have a post width of 1.30 µm. Power absorption efficiencies are almost unity at the designated wavelengths while each pixel would have enough wavelength selectivity to clearly distinguish three colors.



Figure. 9: Three color design found by optimizing three different multimode pixel geometries shown at Figure 8, each with different lithographically drawn dimensions *a*, *g*, and *w*, with identical *d* and R_s . Power absorption efficiencies are almost unity at the designated wavelengths while each pixel would have enough wavelength selectivity to clearly distinguish three colors. *a*, *g*, *d*, and R_s are 6.80 µm, 0.20 µm, 3.14 µm, and 56.6 Ω/square, respectively.

4. CONCLUSION

Infrared wavelength-selective focal plane arrays using planar multimode detectors have been designed using the GA. Such detectors can have high absorption at a specific center wavelength within 7 to 14 μ m infrared band with widely varying bandwidths and can be narrow enough to construct multiple channels within the 7 to 14 μ m infrared band. Tuning of wavelength selectivities by mechanical actuation, and a wavelength-selective three pixel design, each pixel using different lithographically drawn dimensions *a*, *g*, and *w*, with identical *d* and *R*_s have been presented. Changing the wavelength selectivity of each pixel by changing only lithographically parameters would not require a fabrication process with different sacrificial layer thicknesses under different pixels in the array, resulting in a less complex fabrication process.

REFERENCES

- 1 A. J. Stead and M. Missous, "Multicolour infrared detection with In_{0.1}Ga_{0.9}As / A_{10.33}Ga_{0.67}As double and triplecoupled quantum well infrared photodetectors", High Performance Electron Devices for Microwave and Optoelectronic Applications, 1999, EDMO, pp. 119-124, Symposium on 22-23 Nov. 1999.
- 2 Zhengmao Ye et al, "A Normal-incidence InAs self-assembled quantum-dot infrared photodetectors with a high detectivity", *IEEE Journal of Quantum Electronics*, vol. 38, Issue 9, pp. 1234 1237, Sept. 2002.
- 3 H. Hara, N. Kishi, and H. Iwaoka, "Silicon bolometer and micro variable infrared filter for CO2 measurement", Optical MEMS, 2000 IEEE/LEOS International Conference, pp. 139-140, 21-24 Aug. 2000.
- 4 Thomas R. Schimert et al, "Low-cost low-power uncooled 120x160 a-Si-based microinfrared camera for law enforcement applications", *Proc. SPIE*, vol. 4232, pp. 187-194, Feb. 2001.
- 5 S. J. Yoo, *Micromachined wavelength selective microbolometer sensors operating at room temperature*, PhD. Dissertation, The University of Texas at Austin, Dec. 2000.
- 6 J. W. Kim and D. P. Neikirk, "Infrared wavelength selective micromachined microbolometers," *Proc. of SPIE*, vol. 5116 Smart Sensors, Actuators, and MEMS, SPIE's First International Symposium on Microtechnologies for the New Millennium 2003, Maspalomas, Gran Canaria (Canary Islands), Spain, May 19-21, 2003, pp. 514-522.

- 7 D. B. Rutledge and S. E. Schwarz, "Planar multimode detector arrays for infrared and millimeter-wave applications," *IEEE Journal of Quantum Electronics*, vol. QE-17, no. 3, pp. 407-414, Mar. 1981.
- 8 R. L. Eisenhart and P. J. Khan, "Theoretical and experimental analysis of a waveguide mounting structure," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 706-719, Aug. 1971.
- 9 D. M. Pozar, Microwave Engineering, Addison-Wesley, 1993.
- 10 Y. Rahmat-Samii and E. Michielssen, *Electromagnetic Optimization by Genetic Algorithms*, New York, John Wiley & Sons, 1999.