

HgCdTe Photoconductive Mixers for 2-8 THz

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Introduction

Heterodyne spectroscopy has been taken to wavelengths as short as 63 μm with Schottky-diode mixers [Boreiko and Betz 1996]. Schottkys, however, are relatively insensitive compared to superconducting mixers such as the hot-electron microbolometer (HEB), which has an effective quantum efficiency of 3% at 120 μm (2.5 THz). Although HEB sensitivities are bound to improve, there will always be losses associated with antenna coupling of radiation into sub-micron size devices. Another approach to FIR mixer design is to use a photoconductive device which can be made much larger than a wavelength, and thus act as its own antenna. For example, HgCdTe photodiodes have been used as mixers in the $\lambda=10$ μm band for over 25 years [Betz 1981], with sensitivities now only a factor of 2 from the quantum-noise-limit. HgCdTe can also be applied at FIR wavelengths, but surprisingly little work has been done to date. The exception is the pioneering work of Spears (1988) and Kostiuk and Spears (1987), who developed HgCdTe photomixers for the 20-120 μm region.

The spectral versatility of the HgCdTe alloy is well recognized for wavelengths as long as 8-20 μm . What is not so recognized, however, is that theoretically there is no long wavelength limit for appropriately composited HgCdTe. Although Spears (1988) successfully demonstrated a photoconductive response from HgCdTe at 120 μm , this initial effort was apparently never followed up, in part because of the difficulty of controlling the HgCdTe alloy composition with liquid-phase-epitaxy (LPE) techniques. With the availability of precise molecular-beam-epitaxy (MBE) since the early 1990's, it is now appropriate to reconsider HgCdTe for detector applications longward of $\lambda=20$ μm .

We recently initiated an effort to fabricate detectors and mixers using II-VI materials for FIR wavelengths. Of particular interest are device structures called *superlattices*, which offer a number of advantages for high sensitivity direct detectors and very long wavelength heterodyne mixers.

Existing Technology

Only Schottky-diode mixers have been used for heterodyne spectroscopy of astronomical objects at FIR wavelengths. This technology is now considered to be obsolete for high sensitivity observations, and has been supplanted (at least in the lab) with the technology of Hot-Electron micro-Bolometer (HEB) mixers. One of the best HEB results in the wavelength region of interest is the 119 μm (2.5 THz) noise-temperature measurement of the JPL group (Wyss *et al.* 1999). With a niobium HEB mixer cooled to 2 K, they achieved an 1850 K (DSB) noise temperature. From a noise viewpoint, this is equivalent to an effective quantum efficiency (QE) of 0.03 at 2.5 THz. Improvements over the next 2 years are likely to raise the effective QE of HEB mixers to 0.06, with a goal of 0.1. These mixers will remain relatively narrow-band, because of the types of coupling antennas that are used, and the necessity of limiting spectral bandwidth to avoid device saturation. At even higher frequencies, HEB mixers will have difficulty achieving quantum-noise-limited performance because of the increased losses in the antenna coupling structures.

Some work has been done to develop *extrinsic* semiconductors for FIR mixer applications. Park *et al.* (1988) investigated Ga-doped Ge as a heterodyne detector for the $\lambda=100 \mu\text{m}$ region. The low absorption of this material leads to a large detector size of several mm in order to get 10% photon absorption. The large size in turn leads to a long transit time and lifetime for photogenerated carriers. For mixer applications, the carrier lifetime must be short. One technique to speed recombination is to introduce compensation impurities, but this also reduces the photoconductive gain. Regardless, even with high compensation, Park *et al.* (1988) were only able to achieve a 60 MHz IF bandwidth, which is about a factor of 10 less than the minimum needed for remote sensing applications with fixed-frequency local oscillators.

Proposed New Technology HgCdTe

What is needed for FIR wavelengths is an *intrinsic* rather than *extrinsic* detector material. Intrinsic semiconductors have absorption cross-sections 100 times stronger than that of extrinsic (doped) semiconductors. No simple intrinsic materials exist, however, with bandgaps appropriate for $\lambda=50\text{-}150 \mu\text{m}$ detection. Fortunately, one can fabricate intrinsic detectors from mixed materials to obtain a peak photoconductive response at any infrared wavelength. Alloys and superlattices made from HgTe and CdTe can be fabricated with bandgaps engineered between -0.26 eV and +1.60 eV (corresponding to DC to 100 THz response). The absorption coefficient of intrinsic HgCdTe is about 100 cm^{-1} in the $\lambda=50\text{-}150 \mu\text{m}$ range, and so devices as thin as 5-10 μm can provide good quantum efficiency.

Bandgap Engineering

Two approaches are available for the synthesis of “zero-gap” semiconductors. The first is the well-known alloy process in which the bandgap is tailored by varying the mole fraction x of CdTe in an $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ alloy. The second is a superlattice structure, in which the bandgap is determined by the relative thicknesses of alternating HgTe and CdTe layers in a composite semiconductor.

Hg_{1-x}Cd_xTe Alloys

At 77 K, the band gap of the semimetal HgTe is -0.26eV , and that of the semiconductor CdTe is 1.6 eV . These materials can be combined with various fractional compositions x to tune the bandgap $E_g(\text{eV})$ of the Hg_{1-x}Cd_xTe alloy according to the formula (Hansen and Schmit 1983):

$$E_g = -0.302 + 1.93x + 5.35 \times 10^{-4}T(1 - 2x) - 0.810x^2 + 0.832x^3.$$

Figure 1 shows the cut-off wavelength, defined as $\lambda_{\text{co}}(\mu\text{m})=1.24/E_g(\text{eV})$, as a function of fractional composition x at various temperatures. It is evident that by choosing x between 0.16 and 0.17, a wide range of cut-off wavelengths in the FIR can be obtained. For the approximate 0.01 eV band gap needed for 100 μm response, x would be close to 0.17. As the band gap approaches zero, small fractional changes in x lead to large fractional changes in the gap energy, and generally we need to control x to within 0.2% to have a 10% uncertainty in peak response. It should be apparent that compositional inhomogeneities in this case lead to variations in the gap throughout the material resulting in non-uniformity in the response of array detectors. Nevertheless, with MBE deposition techniques adequate control can be achieved. Pioneering work on low-gap HgCdTe alloys by Spears (1988) was done with much less precise LPE techniques, and yet usable photoconductive devices were produced for the 20-120 μm region.

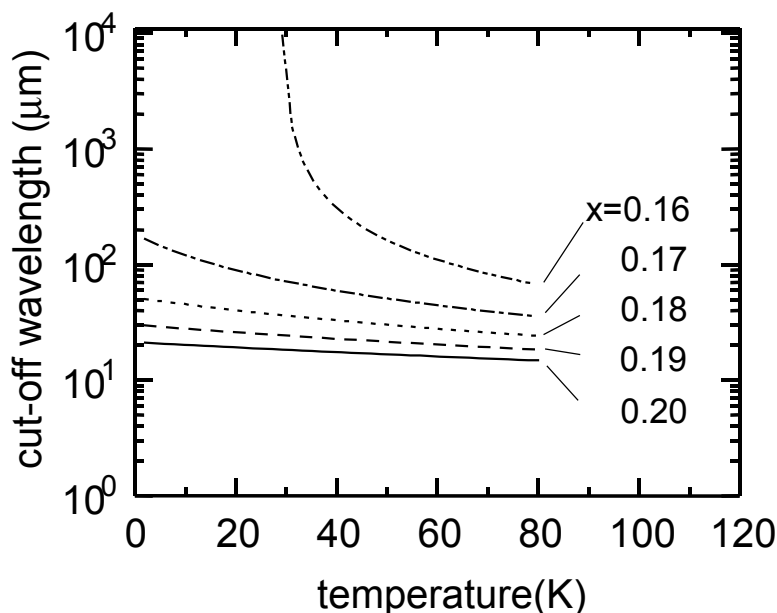


Fig.1: Cut-off wavelength versus temperature for various compositions.

HgTe/CdTe Superlattices

In a superlattice (SL) device, the bandgap is controlled by adjusting the thickness of alternating material layers with very precise molecular-beam-epitaxy (MBE) techniques. Possible material choices are the II-VI compounds HgTe for the *wells* and CdTe (or high-gap HgCdTe) for the *barriers* of the superlattice. Typically, the barrier thickness is 40 Å and the well thickness is many times greater to synthesize a “zero-gap” composite semiconductor. Alternating well and barrier layers are deposited until the total thickness required for the active layer (typically 5-10 μm) is built up. Over a hundred layer pairs are required. Schulman and McGill (1979) first proposed HgTe-CdTe superlattices (SLs) as promising new infrared materials, but few results have been published so far. Since MBE is now a mature manufacturing technology for HgCdTe devices, we believe that it is now possible to fabricate SL structures for FIR applications. We favor the II-VI compounds over III-V materials such as InAs/InGaSb because of their higher electron mobility, which is important for high speed mixers. The UIC Microphysics Lab also has extensive experience with II-VI materials, and a demonstrated proficiency with epitaxial growth on a variety of substrates (Mahavadi *et al.* 1990; Sporken *et al.* 1989; Wang *et al.* 1996).

Superlattices have a number of potential advantages over alloy detectors in the FIR: (i) the band gap of the material is much easier to control; (ii) growth-direction effective masses of electrons and holes in the SL are decoupled from the band gap, so FIR detectors with larger effective masses should display orders of magnitude reductions in the tunneling current; (iii) the carrier degeneracy problem near band edge (longest wavelengths) is less significant; and (iv) a SL can suppress Auger recombination at long wavelengths by intentionally inducing strain.

Although theoretically one can fabricate low band gap SLs from CdTe barriers and HgTe wells, the well thicknesses get large and hard to control for zero bandgap devices. A better approach might be to use HgTe wells and HgCdTe alloy barriers, where the positive gap energy of the alloy is nearly matched to the negative -0.26 eV gap of HgTe. The required +0.26 eV HgCdTe alloy has $x = 0.18$, and is 4 times less sensitive to compositional variations than an alloy with $x=0.168$ designed to work at 0.01 eV directly. Furthermore, possible diffusion of Hg from the wells during processing can be allowed for in designing the deposition process for the barriers. A SL designed with pure CdTe barriers would require more stringent controls on Hg diffusion.

FIR Mixers

Photoconductive materials can be used to make two device types that are applicable as FIR heterodyne mixers: a reverse-biased photodiode (PD), and a DC-biased photoconductor (PC). A heterodyne mixer needs an extremely fast response time to achieve a reasonable IF bandwidth of 2 GHz. Consequently, a PD mixer must be reverse biased with a relatively high field to minimize the device capacitance and to maximize the depth of the depletion region where photogenerated carriers can be collected quickly. Whereas this can be done effectively with high bandgap materials ($E_g > 0.03$ eV), for low-gap materials, the high space-charge field leads to excess tunneling currents that degrade

mixer sensitivity. Of course, for FIR applications, low gap materials must be chosen, and we are left with the PC device structure as our only choice if *alloy* devices are used. A PC mixer can operate with electric field strengths 10 times less than those required by a PD device, provided carrier transit times are kept short, and that means a small interelectrode spacing. On the other hand, if tunneling currents can be reduced as predicted with the *superlattice* structure, then PD devices may become practical out to 100 μm and perhaps 150 μm wavelength.

To minimize the LO power required by a photoconductive mixer, it is important to maximize the current responsivity, or equivalently the photoconductive gain g , given by:

$$g = \frac{\tau}{T} = \frac{\tau\mu E}{d}.$$

Here T is the transit time, μ is the electron mobility, E the applied electric field, τ is the carrier lifetime which sets the IF bandwidth $B=(2\pi\tau)^{-1}$, and d is the electrode spacing. For the high-speed devices of interest here, the maximum value of g is 1 when all the electrons and holes are collected. Another possible condition is that the electrons are collected quickly by the electrodes but the slow moving holes are not. This leads to a condition called minority carrier sweepout where $g(\text{max}) = 0.5$. The electron and hole mobilities of HgCdTe are high ($\mu_e = 10^5 \text{ cm}^2 \text{ V}^{-1}\text{s}^{-1}$ and $\mu_h=\mu_e/200$), and the carrier velocity μE readily saturates at about $3\times 10^7 \text{ cm s}^{-1}$ in HgCdTe.

Given that we also want a minimum IF bandwidth of 2 GHz and hence carrier lifetime of 10^{-10} s^{-1} , the only variable available to adjust is the electrode spacing d . Maximum gain with 2 GHz IF bandwidths requires that d be no larger than 20 μm . On the other hand, a certain detector cross-section D is needed for efficient coupling to an optical field - generally $D=2\lambda$. The solution is to use interdigitated electrodes (IDE) on the detector surface, with the required electrode number N being just D/d . For $\lambda=120 \mu\text{m}$, $D=240 \mu\text{m}$ and we need at least 12 interdigitated electrodes. Surface electrodes are efficient collectors of photogenerated carriers when the absorption depth is not much greater than the electrode spacing. The preferred signal polarization is perpendicular to the long electrode dimension. Another approach would be to couple radiation via a Si immersion lens ($n=3.416$) so that the required mixer size is only 70 μm . These size trade-offs must be considered when designing 8-element heterodyne arrays.

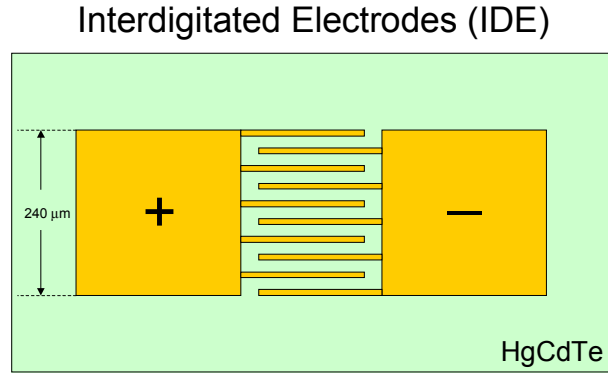


Figure 2: Front Surface View of IDE device

The general expression for the NEP of a photoconductive heterodyne receiver is given by the formula (Kingston 1978):

$$NEP = \left(\frac{h\nu B}{\eta} \right) \left(1 + \frac{P_{Min}}{P_{LO}} \right).$$

Normally, a photoconductive mixer with both generation and recombination noise would have an NEP twice the value given above. However, when recombination is not random, but rather occurs only at the contacts (as with reverse-biased photodiode mixers), then the NEP is as stated. Contact recombination occurs in a photoconductor when the minority carriers are all swept out, and this condition will likely obtain for the IDE devices.

In the NEP equation, η is the quantum efficiency, B is the IF bandwidth, and P_{LO} is the local oscillator power. P_{Min} is the LO power for which the noise power of the LO-induced photocurrent is equal to the input noise power $kT_{IF}B$ of the IF amplifier stage, and is given by:

$$P_{Min} = \frac{2kT_{IF}h\nu}{e^2 g \eta R_{IF}} (1 + \omega^2 \tau^2).$$

Here R_{IF} is the input impedance of the IF amplifier and T_{IF} is its noise temperature. The variable ω is the IF signal frequency. We see that a high value of g (with a maximum of 1) minimizes the required LO power. LO power levels much higher than P_{Min} raise the system gain but do not improve the NEP sensitivity significantly, except at frequencies beyond the -3 dB IF signal bandwidth. This can be seen in Figure 3, where the above power equation is plotted for two sets of conditions. Under ideal conditions ($\eta=1$, $g=1$), and with $T_{IF}=10$ K, $R_{IF}=50\Omega$, and $\nu=3$ THz, P_{Min} is about $2 \mu\text{W}$. With more realistic conditions ($\eta=0.4$, $g=0.5$), P_{Min} is $10 \mu\text{W}$. Even for an array of 8 such mixers, adequate LO power is available from a 1 mW FIR laser coupled via a 10% beamsplitter.

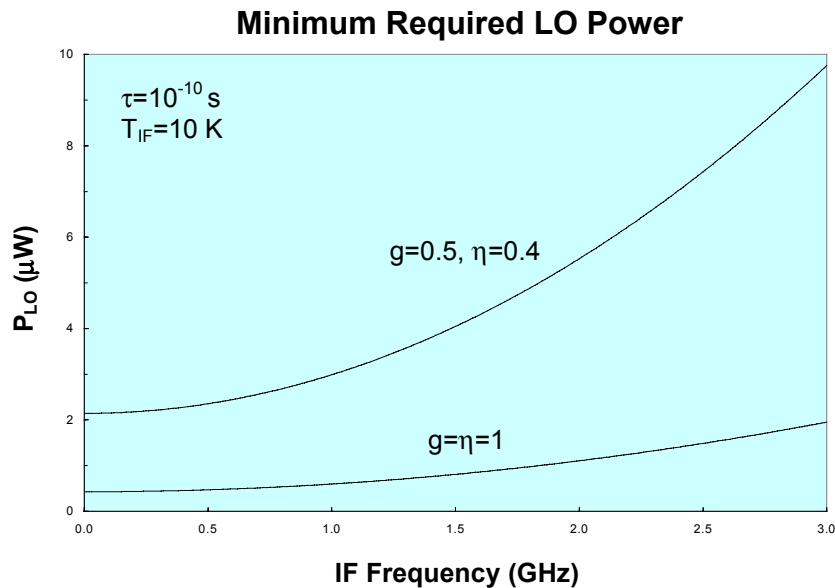


Figure 3: LO Power Requirements

Ideally, p-type HgCdTe should be used to fabricate a PC mixer. The mobility of holes is low enough that a device impedance of $>50 \Omega$ is possible with as many as 10 interdigitated electrodes across a $200 \mu\text{m}$ surface, provided the carrier density at the operating temperature is $< 3 \times 10^{15} \text{ cm}^{-3}$. P-type material also eliminates the conduction band filling problems encountered with n-type material that lead to bleaching of the detector's long wavelength response. Proper control of materials with MBE deposition should allow one to construct a PC mixer with good quantum efficiency (>0.25) over the entire $50\text{-}150 \mu\text{m}$ ($2\text{-}6 \text{ THz}$) band, except for a "dead-spot" between $70\text{-}90 \mu\text{m}$ where HgCdTe has a lattice band absorption.

We can be fairly certain of good results with HgCdTe alloy material because FIR devices have already been made this way. Spears in the late 1980's developed PC mixers with $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ ($x=0.168$) that showed a response as long as $\lambda=118 \mu\text{m}$ [Spears 1988]. At that time only bulk (ingot grown) materials were available, and the exact alloy composition could only be fixed by selection from material with a composition gradient. In addition, that material was n-type, and device impedances were too low for optimal IF coupling. Nevertheless, Spears was successful in demonstrating the utility of IDE biasing and also the use of resonant reflector-enhanced absorption to increase the quantum efficiency to as high as 0.6 in $5 \mu\text{m}$ thick PC devices. Although IF bandwidths between 1.7 GHz and 6.0 GHz were measured for devices with different photoconductive gains, no heterodyne sensitivity tests were made.

Resonant Cavity Enhanced (RCE) Photodetectors

If interdigitated surface electrodes are to be used effectively, the thickness of the absorbing region must be kept smaller than the interelectrode spacing so that photogenerated carriers see high electric fields. This imposes the requirement that the active absorber be less than 10 μm thick. We can use thin absorbers and still get high quantum efficiencies if we put the absorber in a resonant cavity. Figure 4 shows a cross-sectional view of the resonant device structure. A Fabry-Perot cavity is defined by the front surface of the mixer and a suitably spaced rear surface. The reflectance R_1 of the front surface is just the specular reflection from the uncoated material. The rear surface is metallized to produce a reflectance R_2 close to 1. The pure silicon substrate underneath the active region provides the required spacing.

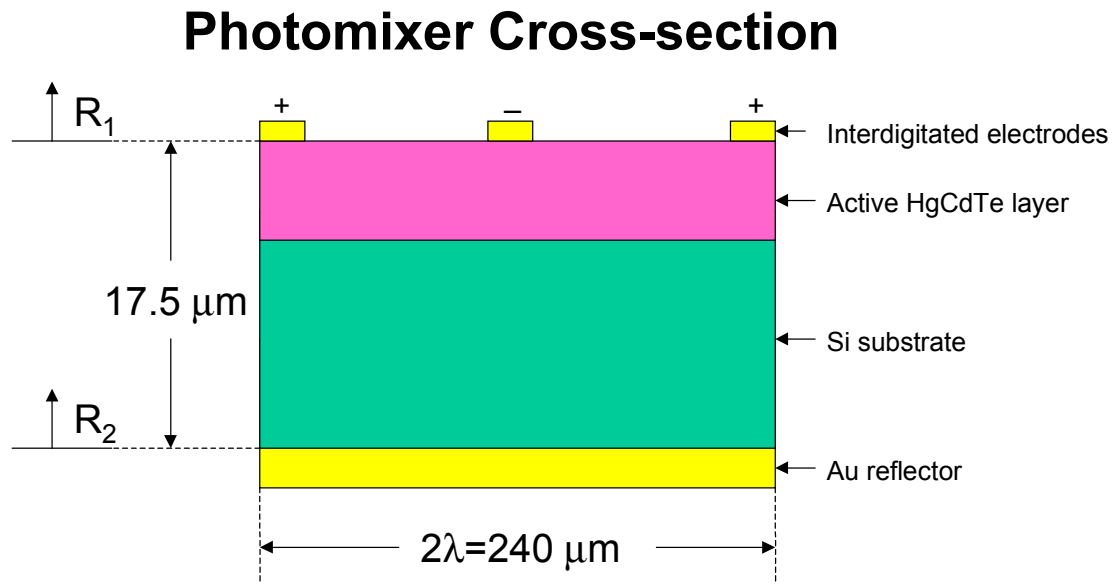


Figure 4: RCE Device Structure

The enhancement in absorption, and hence quantum efficiency, is given by the equation:

$$\eta = \frac{1 + R_2 e^{-\alpha d}}{1 - 2\sqrt{R_1 R_2} e^{-\alpha d} \cos[4n\pi L/\lambda + \psi_1 + \psi_2] + R_1 R_2 e^{-2\alpha d}} (1 - R_1)(1 - e^{-\alpha d}).$$

Here ψ_1 and ψ_2 are the small phase shifts at the two surface reflections (here assumed = 0), α the absorption coefficient, and d the thickness of the active layer. R_1 is the front-surface (power) reflection coefficient, and R_2 is that for the rear surface. The overall device thickness is L , and the average index of refraction is given by n . This equation is plotted in Figure 5 for two sets of conditions. When $R_1=R_2=0$, we have single pass absorption for AR coated surfaces. We see that for realistic conditions we can enhance the quantum efficiency by greater than a factor of 4 over a 16% bandwidth (in first order). Quantum efficiencies greater than 0.4 are possible, and hence heterodyne sensitivities only a few times worse than the quantum limit are feasible. Spears fabricated devices of this type in the late 1980's, but was unable to obtain the high efficiencies predicted here because of low absorption efficiencies at long FIR wavelengths. The n-type material available at the time had excessive conduction band filling (Burstein-Moss effect) that "bleached away" the long wavelength response. This problem can be corrected in MBE work by controlling impurities so as to keep the material p-type with hole densities less than $3 \times 10^{15} \text{ cm}^{-3}$. The low mobility of majority holes also keeps the dark current low and ensures that the IDE device impedance will be high enough for IF matching.

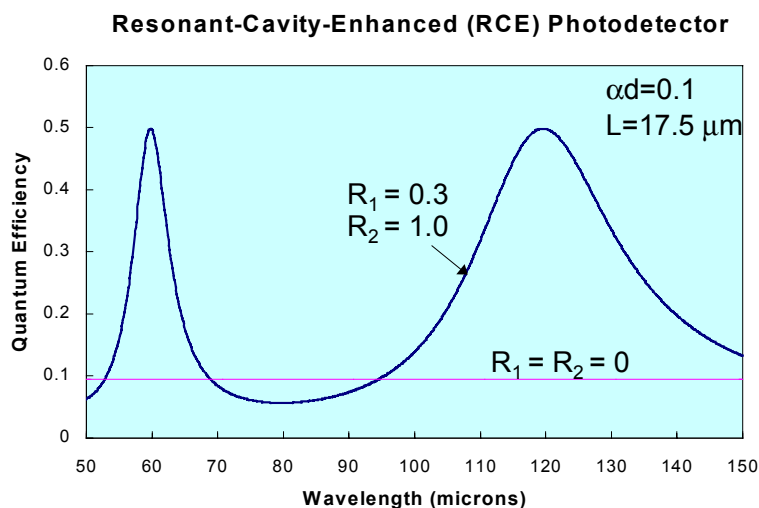


Figure 5: Resonant Enhancement of Quantum Efficiency

We believe that a quantum efficiency of $\eta=0.1$ can be obtained in early generation devices at 3 THz. Our 3-year goal is $\eta=0.4$. At 6 THz ($\lambda=50 \mu\text{m}$), initially $\eta=0.2$ should be possible in a resonant-cavity device structure. The 3-year goal at this wavelength is $\eta=0.6$. A photoconductor (PC) is inherently a broadband mixer for frequencies higher than the energy gap. In contrast to antenna coupled devices, a HgCdTe PC mixer becomes easier to fabricate as the cutoff wavelength decreases.

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