Chapter 1

Introduction

1.1 Background

The difficulty in processing electromagnetic signals near the sub-millimeter wave (SMMW) and far-infrared (FIR) range has presented many challenges to researchers who work in this field. Even though the whole spectrum is governed by the same laws of physics, we often need to deal with only one manifestation of this energy, depending on the wavelength or frequency involved. For example, we can easily transmit and receive radio signals with antennas, where these signals are interpreted as oscillating voltages in an electrical circuit. We can transfer these voltages from one circuit to another through a conductive wire. As the frequency increases, electrical circuits become lossy and inefficient, making it difficult to manipulate voltages above microwave frequencies. At optical frequencies, radiation is often concentrated with lenses or mirrors, and can be piped around though glass fibers. In the optical range, the individual photons of radiation have enough energy to release charge carriers when they are absorbed inside a detector. Since the photon energy decreases as the radiation frequency decreases, it is difficult to detect light as photons at lower frequencies. The SMMW and FIR range corresponds to the intermediate part of the spectrum where neither of these technologies can be readily applied. In the past 20 years, researchers have developed novel and clever techniques to partially overcome some of the problems associated with this region of the spectrum. Some of the most interesting are the quasi-optical systems which use lenses to focus radiation into antenna structures.

Unlike radio and television, many of the technologies which involve the SMMW and FIR part of the spectrum remain outside the public domain, and most are limited to military and research applications. Many of these devices require very complex instrumentation that gives us somewhat primitive performance compared to devices which work in other regions of the spectrum. For example, a three element stressed Ge:Ga photoconductor array for the Infrared Telescope in Space (IRTS) satellite was recently developed [1], which will be used to observe wavelengths near

158 μm in deep space. This detector operates at 2.0 Kelvin while uniaxially stressedwith springs, and optimally collects data at a rate of two hertz. In contrast, a TV CCD video camera is now available to the general public (via mail order [2]) for $150, which operates in the visible and near infrared (IR).

Despite the difficulties and cost associated with SMMW and FIR technologies, there are many applications to drive development of receivers and imaging systems for this spectral region. Much of the original work in this area has been driven by military applications. During World War II, there was an intense effort by the United States and Great Britain to develop radar technology with microwaves. Today, there is interest in developing imaging, guidance, and surveillance systems using millimeter waves, since the smaller wavelength would allow higher resolution than conventional radar. Millimeter and SMMW offer an advantage over infrared imaging systems in that they are able penetrate clouds, dust, and smoke.

There are several applications in the field of remote earth sensing that would benefit from improved systems in this spectral range. Recently, there has been much publicity about the controversial issues of possible global warming and ozone depletion. Ozone has many strong spectral lines between 100 GHz and 300 GHz, and can be monitored by orbiting satellites and ground based stations[3]. By using a technique called "limb sounding," many other trace elements can also be monitored in the stratosphere[4]. This technique can be used to monitor such reactive species as chlorine monoxide at 204 GHz, and the hydroxyl radical (OH^-) at 2.5 THz. New detectors may also clear up issues involving the stability of the earth's climate, and the influences of carbon dioxide. Global warming proponents claim that increased carbon dioxide emissions since the industrial revolution are contributing to a destabilization of the earth's climate. Since CO_2 is a strong absorber of infrared radiation, it is argued that the increase in CO_2 levels may be increasing global atmospheric and oceanic temperatures. The oceans would then release more CO_2 into the atmosphere due to the decreased solubility of CO_2 in the heated water and cause more heating. However, the increased cloud cover from warmer temperatures might be expected to stabilize any increase in global temperatures. Cloud effects on atmospheric temperature are poorly understood, but are generally known to provide significantly cooler daytime temperatures at ground level. Current computer models of global climate do not accurately account for the effects of increased cloud cover. Depth profiles of temperature can be obtained by using 60 GHz (oxygen absorption) sensors, while water vapor can be monitored near 22 GHz[4]. Global rain precipitation rate can be monitored near 30 GHz, where the wavelengths match the diameters of falling raindrops[4]. In addition to atmospheric studies, remote earth sensing systems are also used for crop monitoring, finding ground water and mineral resources, and measuring sea temperatures[5].

SMMW and FIR detectors are also used in astronomy to study galactic clouds [6] , background radiation, and other energy sources in space. A FIR microbolometer array has also been used to study plasma systems [7].

1.2 Detector Systems

Most detector systems can classified into three categories: 1) Rectifiers, 2) Photon detectors, and 3) Thermal devices. Figure 1.1 shows the approximate spectral range of some common types of detectors used throughout the microwave and visible range. In addition to the different spectral ranges, all of these devices have distinct detection characteristics which affect the usefulness for various applications.

Antenna-coupled schottky diodes are often used as rectifying detectors throughout the lower part of the range shown in the graph. These devices are usually limited by parasitic capacitances of the diode or from the antenna leads. Whisker contacts are often used to create very small schottky diodes for microwave applications, however, they are not easy to implement for remote or harsh environments. In order to extend their range of operation, some researchers have used advanced lithographic techniques to fabricated airbridge anodes to contact the top side of the diode[8]. Schottky diodes can be used with mixers to act with heterodyne receiver systems. This type of detector offers advantages for narrow band spectral analyses, but has an upper cut-off frequency in the sub-millimeter range.

Photon detectors are well developed in the visible range, and most types can be easily integrated into two dimensional arrays for imaging systems. In these detectors, the energy of a single photon can be absorbed to excite a bound electron across a forbidden energy gap to a free state. A signal is detected as the current induced by photon absorption. The photon energy must be slightly higher than the band gap in order for this mechanism to occur, therefore low band gap materials must be used in order to capture low energy photons.

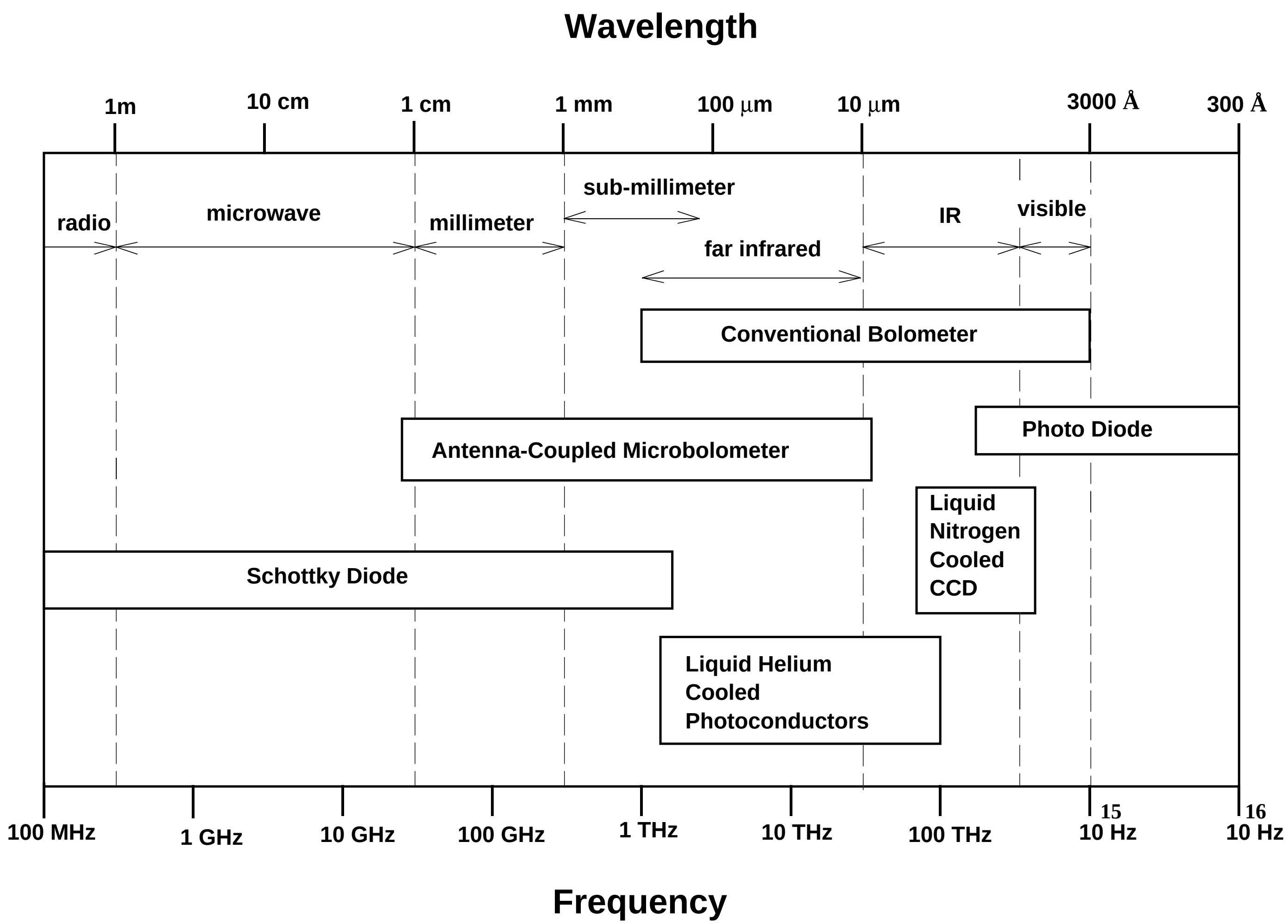

Figure 1.1 Spectral Range of some common microwave and optical detectors.

Room temperature photon detectors have problems detecting wavelengths below a few microns because the band gap is low enough so that thermal energy can significantly excite electrons above this gap. By cooling these detectors, they can be made to operate at lower frequencies, provided a proper band gap material can be found. Most of the low band gap materials are extrinsic, in which the photons are used to excite shallow impurity states. Very shallow band gaps can be induced by uniaxially stressing the crystalline lattice. Stressed Ge:Ga has been used to detect wavelengths as low as ~ 180 μm for the Infrared Telescope in Space[1], however, they are somewhat slow (~2 Hz), and must be operated at 2.0 K. They are also very difficult to operate, with a resistance of ~10^{13} Ω, a breakdown voltage of ~ 40 mV, and an operating current near $3\text{x}10^{-14}$ A. However, these detectors are quite sensitive, with an noise equivalent power (NEP) < $5 \text{ x } 10^{-18}$ W/Hz$^{1/2}$.

One type of thermal detector is the bolometer, which changes resistance when heated by radiation. Typical bolometers are simple devices, consisting of a thin film of material whose resistance is sensitive to temperature changes. The film area dimensions must be larger than the wavelength in order to efficiently absorb radiation. Since some bolometer films are transparent, a thin film of absorbing material is sometimes used to coat the surface of the bolometer. These devices work well as broad band detectors throughout the FIR, however, these devices tend to be slow (~1 - 500 Hz), and have low responsivities. For wavelengths longer than ~ 20 μm, most bolometers are cooled to near liquid helium temperatures to reduce thermally generated noise.

1.3 Microbolometer Systems

Microbolometers are broad band thermal detectors, which use an antenna to couple power into a small load resistor[9]. The resistor acts as a tiny bolometer which changes resistance when heated. Since the radiation is captured by the antenna, the microbolometer detector element can be much smaller than the wavelength of the incoming radiation, unlike large area bolometers. The antenna and the detector can be defined on a chip using standard lithographic techniques to produce very small detectors. These small devices can have large thermal impedances which produce a relatively large change in temperature for a given amount of power. The smaller thermal mass allows faster heating and cooling times, for near MHz operation. The result is that these devices have higher responsivities, and operate much faster than conventional bolometers. Bismuth has generally been used as the detector element for most microbolometers. 2 μm x 4 μm room temperature bismuth microbolometers generally have a responsivity near 20 V/W, and an NEP near 10^{-10} W/Hz$^{1/2}$. Figure 1.2 illustrates a typical microbolometer configuration using a modified bow tie antenna.

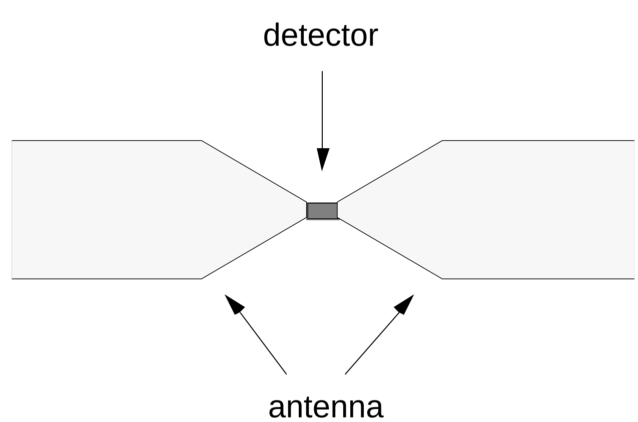

Figure 1.2 Bismuth microbolometer using a modified bow tie antenna

In order for a microbolometer to absorb high frequency power from an antenna, the microbolometer resistance must match the imbedding impedance of the antenna, otherwise power will be reflected from the load. Bismuth is generally used as the detector material for microbolometers because it is one of the few materials whose thin film resistivity ($\rho \sim 500 - 900\ \mu\Omega$-cm) readily allows for impedance matching to typical planar antenna impedances of 100 to 200 Ω. Composite microbolometers have been demonstrated [10] in which the temperature sensing element is in close thermal contact, but is electrically isolated from the antenna load. This design allows the use of materials which can be freely chosen to maximize the sensitivity of the detector. Figure 1.3 shows one composite microbolometer configuration.

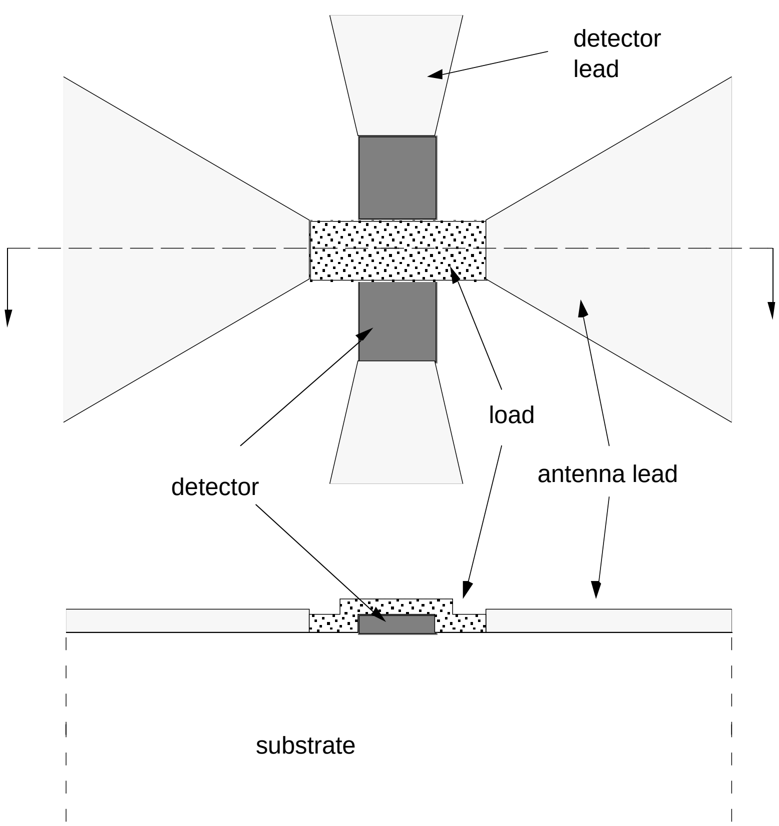

Figure 1.3 Top view and cross-section of a composite microbolometer. The load is impedance matched to the antenna, and is thermally coupled to the detector.

Antenna characteristics are affected tremendously by the substrate. Since an antenna couples much more strongly into a dielectric material than into air, radiation is fed into the detector from the back side of the substrate. Hemispherical and hyperhemispherical substrate lenses are often used with microbolometer systems in order to eliminate surface waves within the substrate[11]. The substrate and lens must have the same dielectric constant for this effect to work. On the down side, substrate lenses can cause absorption and reflection losses. Reflection can be reduced with optical coatings; however this will attenuate frequencies which are incompatible with the coating. Figure 1.4 shows a quasi-optical system used for implementing antenna-coupled microbolometers. If an objective lens is used, the aperture of the objective should be matched the exit pupil of the substrate/lens system. Any mismatch will cause additional losses in the system. Low dielectric constant substrates will usually provide a better feed pattern for the optics, and give a better overall system coupling efficiency. A twin slot antenna structure has been studied and tested which operates without a substrate lens, with low surface wave losses[12-14].

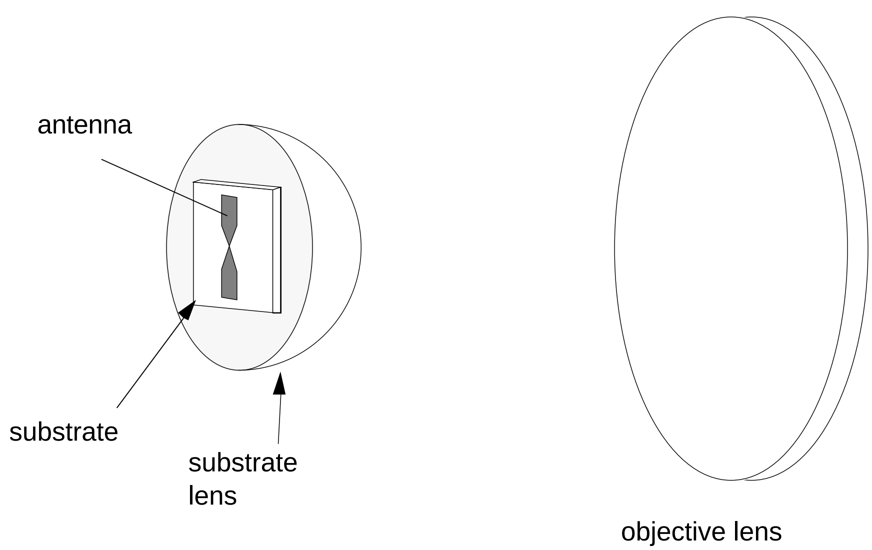

Figure 1.4 Quasi-optical system for implementing antenna-coupled microbolometers

1.4 Overview of Work

There are many issues which affect microbolometer performance. Understanding these issues is important for designing and optimizing these detector systems. One must be able to understand and predict the effects of material properties and device geometry. Chapter 2 reviews, evalutes, and expands the theory behind microbolometer responsivity performance. Analytical models of microbolometer thermal impedances are presented in detail. Results from numerical simulations were used to quantitatively compare the influence of different independent components of heat flow from typical bismuth microbolometer structures. Heat flow directly into the substrate is usually the dominant mechanism governing the net thermal impedance from most conventional microbolometer structures. The substrate thermal impedance has previously been modeled by using a hemispherical approximation[15]. The accuracy of this model was measured by using a three dimensional finite difference numerical method. This numerical method was also used to study the effect of the detector length-to-width aspect ratios on the substrate thermal impedance. The results from the numerical modeling were used to create an new empirical formula for a more accurate approximation which also accounted for abitrary length to width aspect ratios. This is an important consideration for material selection because the resistivity of the material may affect the aspect ratio of the detector dimensions.

The second section of Chapter 2 reports a theroretical investigation into the issues that affect microbolometer responsivity. This study shows that it is important to know the limiting mechanism of microbolometer operation in order to more accurately predict the effect of physical parameters on device performance. A quantitative parametric analysis of responsivity is given for a variety of limiting mechanisms. Calculations shown here suggests that electromigration is the primary mode of failure for conventional metallic microbolometers and should be considered when optimizing geometries and material choices.

Chapter 3 details how a three dimensional finite difference technique was used to quantitatively model the thermal properties of various microbolometer devices. Both steady state and transient analysis techniques are discussed. A new numerical algorithm was developed for this study to compute transient thermal profiles. The mathematics behind this algorithm is explained in this chapter. This algorithm was tested on systems which could be solved analytically.

In chapter 4, a study using a high temperature superconductor as a composite microbolometer detector material is discussed. Results from numerical simulations and experiments are presented.

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