HOT ELECTRON DETECTION AND MIXING EXPERIMENTS IN NbN AT 119 MICROMETER WAVELENGTH

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ABSTRACT

We have performed preliminary experiments with the goal of demonstrating a Hot Electron Bolometric (HEB) mixer for a 119 micrometer wavelength (2.5 THz). We have chosen a NbN device of size 700 x 350 micrometers. This device can easily be coupled to a laser LO source, which is advantageous for performing a prototype experiment. The relatively large size of the device means that the LO power required is in the mW range; this power can be easily obtained from a THz laser source. We have measured the amount of laser power actually absorbed in the device, and from this have estimated the best optical coupling loss to be about 10 dB. We are developing methods for improving the optical coupling further. Preliminary measurements of the response of the device to a chopped black-body have not yet resulted in a measured receiver noise temperature. We expect to be able to complete this measurement in the near future.

I. INTRODUCTION

The on-going development of Hot Electron Bolometric (HEB) mixers [1,2,3,4] is ultimately justified by the fact that such mixers are predicted to achieve lower receiver noise temperatures than existing receivers, starting at frequencies of about 1 THz. SIS mixers are now the lowest-noise receivers up to about 700 GHz, and are making progress in achieving lower receiver noise temperatures between 700 GHz and 1 THz (see Figure 1). At 1 THz and above, the thin film superconductor version of the HEB mixer will have the advantage of not being limited to frequencies below or close to the bandgap frequency

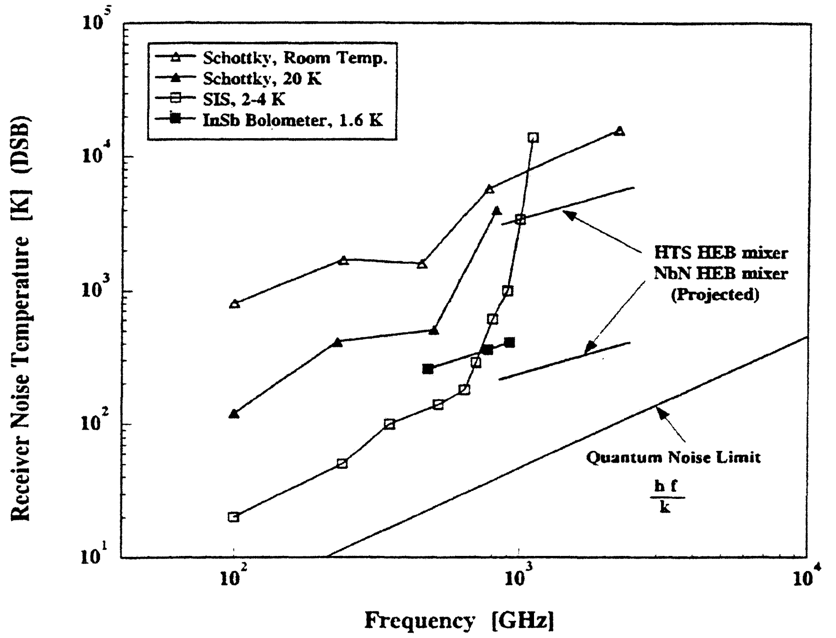

Figure 1: Receiver noise temperature for receivers in the THz frequency range.

of the superconductor. It is appropriate that the initial exploration of HEB mixers takes place at frequencies up to a few hundred GHz, until enough has been learned about the properties of hot electrons (quasi-particles) in thin film superconductors, but at some point an actual THz HEB mixer need also be explored. This paper describes the initial phase of this type of an investigation. We chose to work with NbN films, which have demonstrated IF bandwidths close to 1 GHz as reported in earlier papers; two papers presented at this conference describing millimeter wave NbN HEBs now report IF bandwidths of 2 GHz [5,6], and further studies are likely to improve on this number. The IF bandwidth of NbN HEB mixers thus is now in the range where it can be expected to meet the requirements of practical THz receivers. Additionally, the receiver noise temperature of NbN HEB mixers is predicted to be in the same range as that demonstrated in Nb HEB mixers [3,4]. These facts identify NbN as the most promising HEB material in which the hot electrons in the device are cooled by emission of phonons to the substrate [2].

Submillimeter gas lasers, pumped by CO_2-lasers, can produce output powers of a few mW to 100 mW or more at discrete frequencies from 1 to several THz. They are thus ideal laboratory sources of LO power for initial experiments with NbN HEB mixers. We have chosen to work with the 118.83 micrometer wavelength line of methanol (a frequency of 2.52 THz), using a modified Apollo laser, making it possible to utilize direct focusing of the laser onto a device of size 700 micrometers by 350 micrometers as shown in Figure 2. The device consists of about 175 strips of NbN, which have a width of 1 micrometer and are spaced by 1 micrometer. Since the strips are very narrow compared with the wavelength, the device

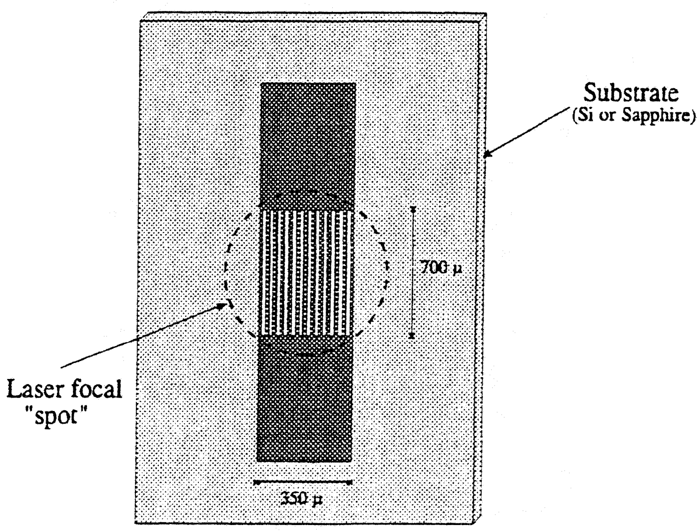

Figure 2: NbN device for 2.5 THz mixer.

absorbs THz power as a uniform resistive sheet. The device size was chosen to match the size to which the laser beam could easily be focused.

We have demonstrated strong detection in this device at 2.5 THz. We have also developed methods for obtaining good optical coupling to a large device of this type, even when the equivalent surface resistance of the film is quite high (several kΩ/square). The theoretical coupling has been derived and agrees with our preliminary measurements. Further experiments will be performed in the near future which are expected to demonstrate improved coupling. We also describe our preliminary attempts at measuring the receiver noise temperature of the mixer and our plans for future experiments.

II. DEVICE FABRICATION

The devices were fabricated from NbN films which were from 30 to 70 Å thick. The NbN films are DC magnetron sputtered on substrates of either silicon or sapphire. We chose these substrates since it had been shown [7] that thin NbN films on these substrates have high critical temperatures (T_c) and a sharp transition (ΔT_c). Theory indicates that the highest conversion gain is obtained for films with small ΔT_c. In contrast, almost all other work on NbN HEB mixers has been performed with NbN on quartz substrates which generally results in lower T_c values and a wider transition. Typical films on sapphire have T_c of about 14 K for $t = 70$ Å and 12.5 K for $t=50$ Å. The transition width may be as narrow as 0.2 K for 70 Å films and 0.35 K for 50 Å films. Surface resistance values for the films vary from 220 Ω/square for 70 Å thickness to 420 Ω/square for 50 Å. The devices should have a surface resistance of about twice these values due to the 50% filling factor. Transition temperatures for films on silicon are slightly lower, and ΔT_c's slightly wider compared with films of the same thickness on sapphire. The NbN films remain superconducting down to 30 Å thickness, with T_c values above 4.2 K. The particular range of thicknesses was chosen in anticipation of achieving bandwidths of 1-2 GHz. Generally, the thinner films have wider bandwidths until a limit is reached, for which the bandwidth becomes independent of the thickness. The critical thickness for which this happens is known for Nb, but not for NbN, on the above substrates. The quality of the films is also important for good mixer performance and has been steadily improved in the last couple of years. We are in the process of measuring the bandwidth of devices with different film thickness in a microwave setup [8]. Experience with microwave measurements on other HEB mixers indicates that the bandwidth measured is close to that found in actual mm-wave mixers [6].

The devices are contacted by pressing indium onto the contact regions. They are then mounted onto a copper post, which is connected at the other end to the cold plate of an IRLABS liquid helium dewar. A heater and temperature sensor are also attached to the copper post close to the device.

III. OPTICAL COUPLING TO LARGE DEVICES

In order to calculate the optical coupling to one of our devices, we use a plane wave approach. Plane wave propagation in the different media involved is modeled by TEM transmission lines of the appropriate impedance with the help of a commercial software package (Hewlett-Packard's MDS). We have studied three configurations, as shown in Figure 3a, 3b and 3c. The configuration in Figure 3a is the NbN film on a substrate, which has thickness of about 0.5 mm. The fraction of optical power coupled to an infinite film as a function of the surface resistance of the film is plotted in Figure 4 (the dotted curve). Note that the surface resistance of the film at 2.5 THz is equal to or a little less than the normal state surface resistance, since the frequency is well above the bandgap frequency.

Improved coupling can be obtained by forming a λ/4 coating on the back side of the substrate as indicated in Figure 3b and Figure 4 (the full drawn curve). The radiation should then be incident from the coated side. We have produced a film of the required thickness (16μm) by spin coating with the polymer PPQ (polyphenylquinoxalin)[1]. Three consecutive spinnings are required. PPQ has a refractive index of 1.76, measured in the visible region. Its exact THz properties will be measured in the near future, but are not expected to differ very much.

A second method for matching THz power to a large device can be used in the case of silicon substrates (see Figure 3c). This method consists of etching a well in the silicon substrate behind the device to a depth such that the remaining thickness is $\lambda/4\sqrt{\varepsilon_r} \approx 8.7\mu m$ and then covering this well with conducting metal. The well forms a "back-short" behind the device which is particularly effective in improving the coupling to a thin film device, as demonstrated in Figure 4 (the dash-dot curve). We are presently experimenting with techniques for etching such back-shorts. The calculations in Figure 4 have been done for silicon substrates; very similar results would be obtained for the sapphire case, since the dielectric constants are quite close. There will also be another factor involved in the optical coupling to the actual device which can be obtained by convoluting the (gaussian) form of the laser focal spot with the shape of the device. This factor is roughly 50% or a little larger.

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[1] PPQ is a trade name of the CEMOTA Corp., Vernaison, France

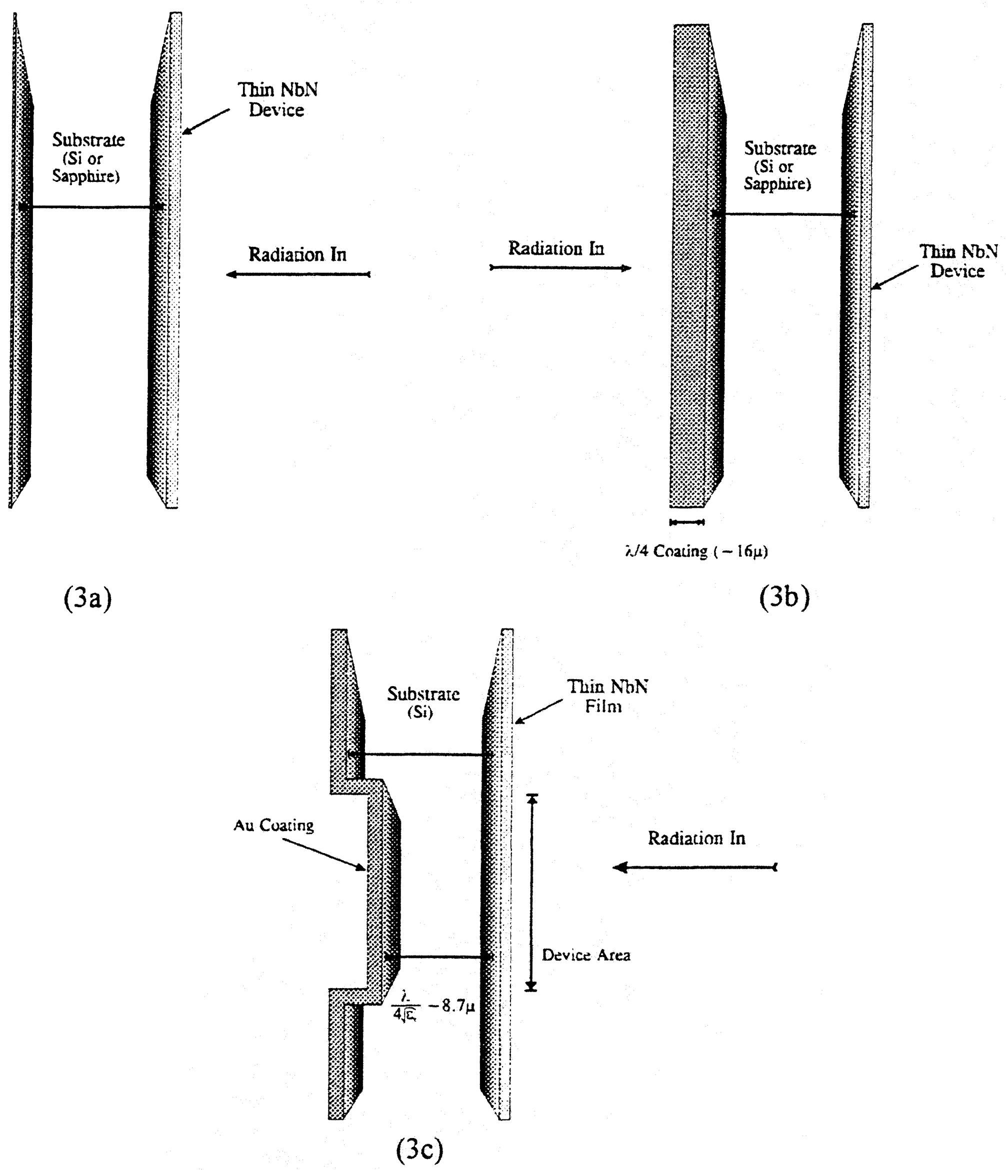

Figure 3: Different configurations for 2.5 THz NbN mixers: a) with no matching layer. b) with PPQ matching layer. c) with etched "back-short".

IV. OPTICAL SETUP

The optical setup is arranged as shown in Figure 5. The THz laser has a maximum output power of 100 mW (CW) on the 119 μm line. The laser power output was increased to this level by utilizing a capacitance grid type uniform output coupler [9]. A mylar beam splitter transmits 40% of the laser power, while diverting 60% into a matched load. The laser beam is then focused by an off-axis paraboloidal mirror through a 0.75 mm polyethylene widow into the dewar. Shorter IR wavelengths are further

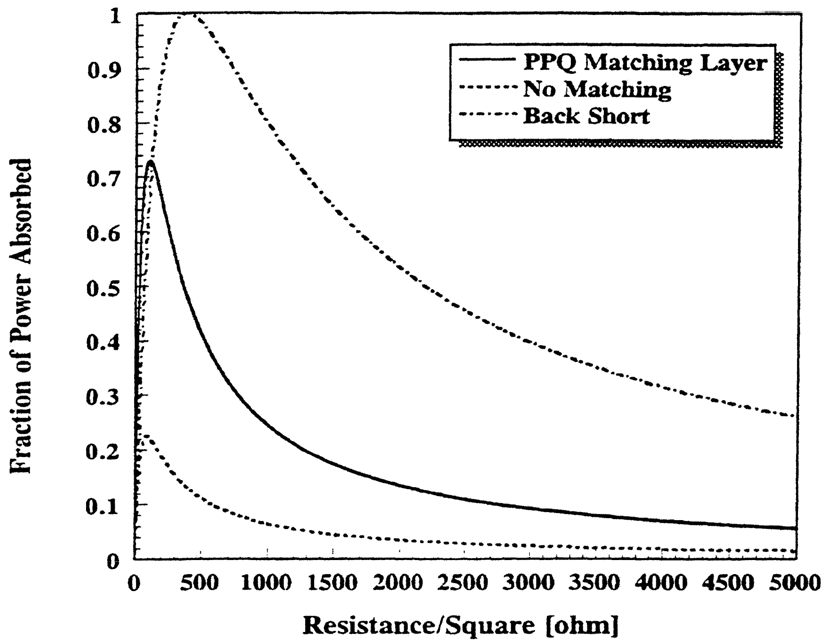

Figure 4: Power coupling to NbN device for different configurations.

attenuated by a sheet of black polyethylene at 77 K. The beamsplitter allows radiation from a hot-cold load to be directed into the beam path. This blackbody radiation is derived by chopping between a room temperature absorber and a liquid nitrogen bath. The device is biased through a cold bias tee connected through an isolator to a broadband cooled HFET amplifier with close to 30 dB gain and about 90 K noise temperature (including isolator losses). The IF system bandwidth is limited by the circulator to 950 - 1400 MHz. After further amplification, the IF power is measured with a microwave detector followed by a lock-in amplifier with its reference derived from the chopper.

The setup is aligned by using the HEB device itself as a detector and observing the signal through the bias port. The device is biased close to T_c for maximum responsivity, which is of the order of 10's of V/W. This makes it easy to find the detector position and maximize the detected signal for alignment.

V. EXPERIMENTAL RESULTS AND DISCUSSION

We have detected the effect of the laser power on the IV-characteristics of two devices: Device A with R/square of 5 kΩ and device B with R/square of 1 kΩ. These initial devices have somewhat lower T_c's and also a higher resistance. The predicted optical coupling factors for the two devices are about 1.5% and 7%, respectively. The actual coupled power can be measured on the I-V curves by using the assumption that DC and RF power have identical effects in terms of heating the electrons [3]. An example of measured I-V curves is given in Figure 6. The laser power incident outside the dewar window was measured with a large area power meter. In the recording of Figure 6, the power absorbed by the device was 2 mW while the power measured in front of the offset paraboloid mirror was 20 mW. We can thus estimate a total optical coupling loss of 10 dB, which includes small losses in the window and the black polyethylene sheet. Similar measurements for device A gave 20 dB total optical loss. These values agree quite well with theoretical predictions. The coupling loss may be improved slightly with the range of resistance values that are possible with films of thicknesses up to 70 Å. However, a more substantial improvement can be obtained by using the matching techniques described in Section III. From Figure 4 we can predict coupling loss of 4 to 5 dB by using the PPQ layer, and better than 1 dB with the backshort technique. We are in the process of preparing for such experiments.

With the present optical coupling loss of 10 dB, it should possible to measure the receiver noise temperature. The first such measurements have resulted in extraneous signals in which a fraction of the laser power is diverted toward the chopper and gives rise to a modulation of the power at the detector, which in turn changes its impedance and sends a chopped signal through the IF amplifier. Further

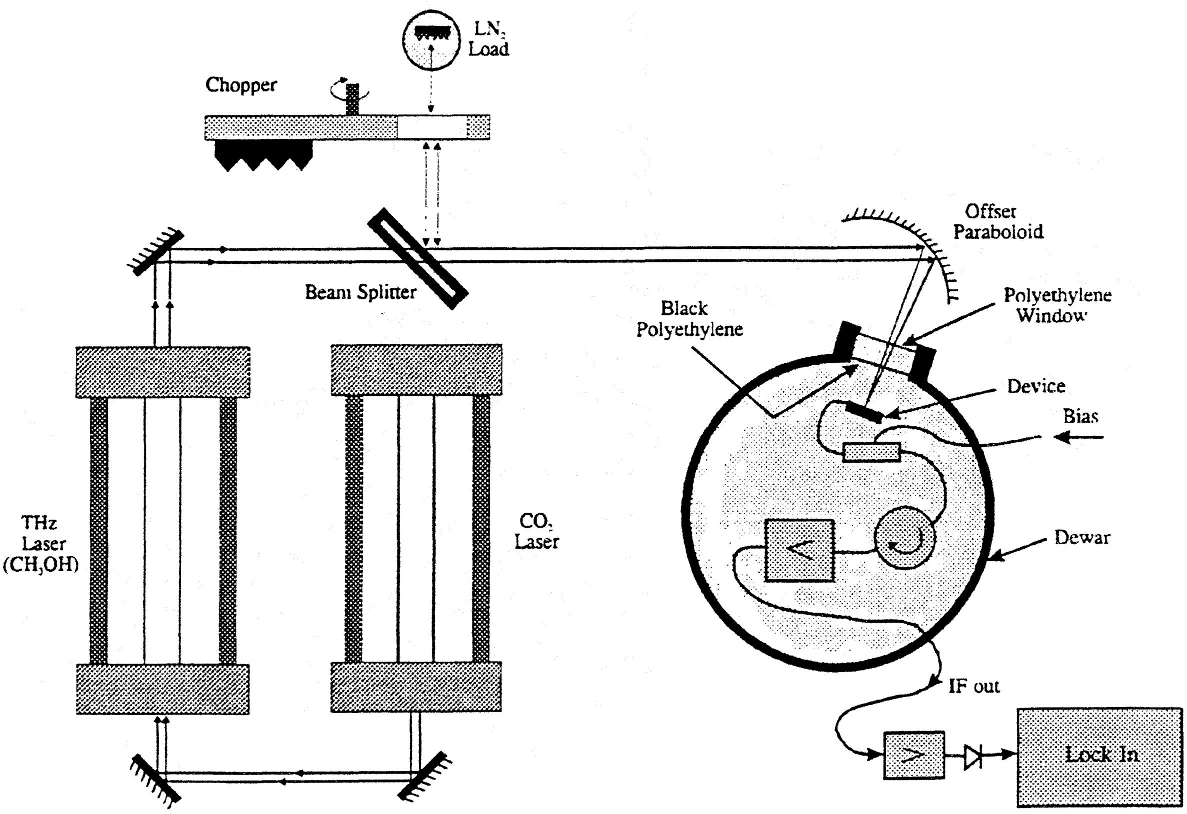

Figure 5: Optical layout of the noise temperature measurements.

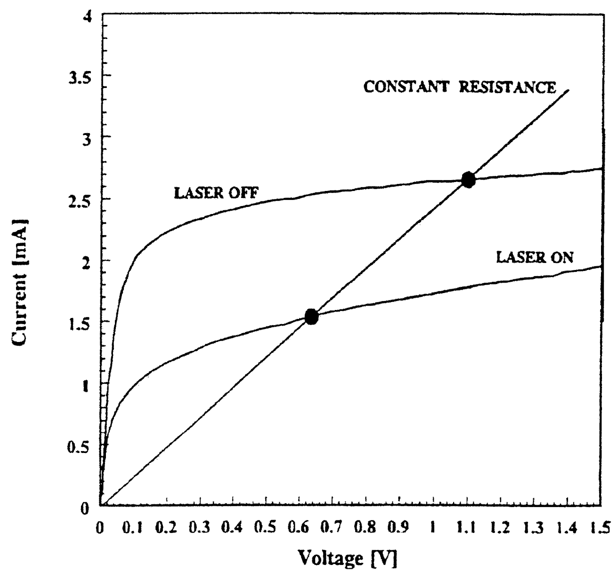

Figure 6: IV curves for NbN device at 11.3K. (T_c=11.8K)

refinements in the system will eliminate such extraneous signals and allow us to measure the noise temperature of the mixer.

A more convenient method of measurement for THz mixers involves the use of two laser sources. This can be accomplished by using laser lines from different gases which have accidental near-coincidences. A more elegant technique utilizes a sideband generator such as the one described by Mueller and Waldman [10]. This configuration is illustrated in Figure 7. In our future experiments we also plan to focus the laser and blackbody power through an extended hemispherical lens and couple a device to a log-periodic antenna behind this lens. The LO power required will then decrease to the μW level, due to much smaller size of the device in this case.

VI. CONCLUSION

We have shown that 2.5 THz laser power can be coupled to a large (700 x 350 micrometer) NbN HEB device with a best coupling loss of about 10 dB. The changes induced by the laser power on the I-V curve of the device are similar to those obtained in efficient NbN mixers operated at lower frequencies, which leads us to believe that we should be able to demonstrate mixing in this device. Experiments are under way to improve the optical coupling further and to measure the receiver noise temperature.

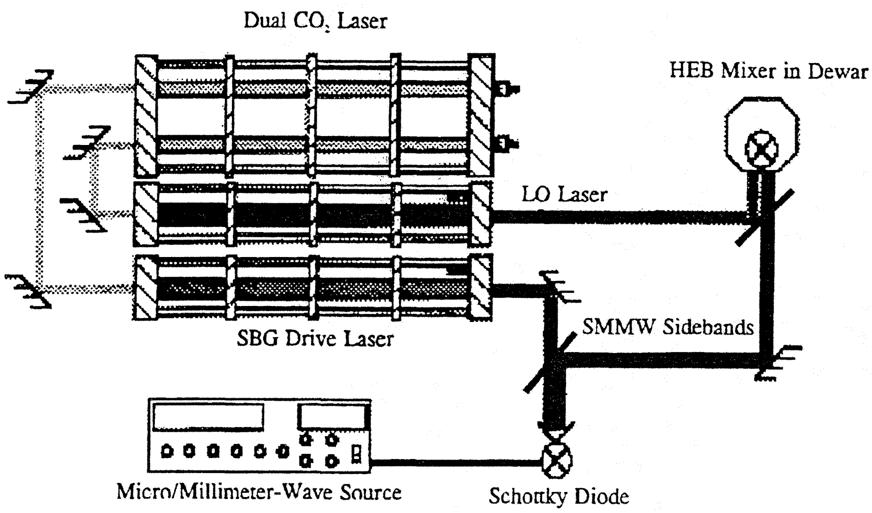

Figure 7: Configuration of a sideband-generator.

VII. ACKNOWLEDGMENTS

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