ELECTRON AND PHOTON TUNNELING TRANSDUCERS FOR GRAVITATIONAL WAVE ANTENNAE

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ABSTRACT

We show applications of electron and photon tunneling transducers for detecting small displacements in resonant bar gravitational wave detectors. A single-crystal silicon bar detector of mass 150 kg instrumented with a multimode tunneling transducer may reach $h = 6\times10^{-19}$ while operating continuously at room temperature.

1. Introduction

Active transducers have introduced new dimensions in the design of gravitational wave detectors. The electromechanical equivalent of transistors, active transducers are non-reciprocal and have available power gain. Transducer gains can exceed 10^9 so the gravitational wave antenna is virtually immune to the fluctuating back-action force from the noise in following amplifiers.

An example of an active transducer is the electron tunneling transducer proposed by Niksch and Binnig[1] and analysed by Bocko et al.[2]. A working device was demonstrated by Bordoni et al[3]. Such transducers should be quantum limited although in practice there is excess 1/f noise in the kilohertz frequency range of gravitational wave antennae. Another example is a photon tunneling transducer[4]. This latter transducer uses a combination of a prism and resonant cavity. A laser provides a quantum-limited source of photons. A small gap between planar surfaces acts as a tunneling barrier for photons which are then injected into a total internal reflection monolithic resonator (see Figure 1). Prototype photon tunneling transducers have been built.

2. Gravitational Wave Antenna Instrumented with Tunneling Transducers

In an earlier paper[5] we showed that active transducers allow vast improvements in the sensitivity of room-temperature gravitational wave detectors. This improvement is possible because antennae equipped with active transducers are not amplifier limited, rather the detector burst noise temperature, T_n, is limited by the Brownian noise of the antenna itself. The Brownian noise may be reduced by using a short integration time - limited only by the bandwidth of the antenna. Two properties make single-crystal silicon the preferred material for room-temperature antennas. The speed of sound in silicon is v_s = 9000 m/s (compared with 5500 m/s for aluminum), and at room temperature the mechanical Q of a silicon bar can be 20 million[6]. The strain sensitivity of an antenna goes as $T_n^{1/2}\, m^{-1/2}\, v_s^{-2}$. Therefore the strain sensitivity of a 1000 kg aluminum antenna is matched by a 140 kg silicon antenna of the same noise temperature. 150 kg single-crystal silicon cylinders have been grown.[7]

3. Wide-band Antenna

In order to verify these ideas we have built a prototype aluminum (5056) wide-band antenna. Its effective mass is 75 kg. It is a three-mode antenna made from a dumb-bell and two tuned torsional resonators. The torsional resonators are cut from a massive piece of 5056 aluminum which is then bolted to the end-face of the dumb-bell. The oscillation frequencies of the resonators are tuned during fabrication. The smallest oscillator is cut first and the springs are trimmed until the right frequency is reached. The second oscillator is cut next. The second set of springs is trimmed until the two coupled frequencies have a minimum spread. When this condition is satisfied the two oscillators have equal intrinsic frequencies. Using this technique we reached the design objective of having equal intrinsic frequencies for all three oscillators. The values of the two intermediate masses were calculated by maximizing the signal to noise ratio for a given shot-noise of the active transducer[5]. In Figure 2 we show the multimode oscillator. It is evident that this 'nested' geometry can be extended to several oscillators with successively decreasing masses. In fact we have built a four-mode oscillator.

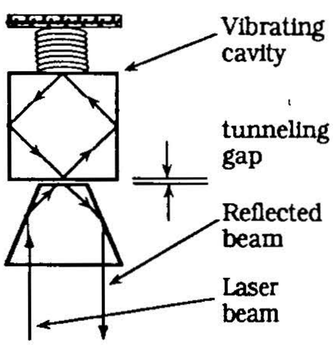


Figure 1 Photon tunneling transducer

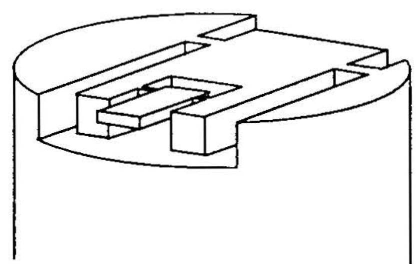


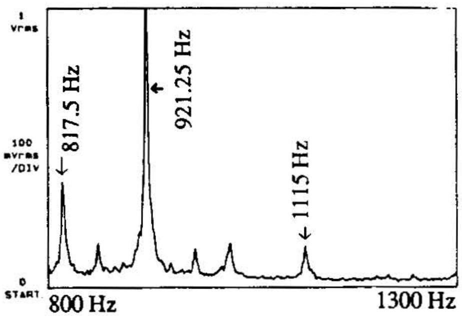
Figure 2 Two-mode torsional oscillator

The Q of each of the three modes is ~10^5 at room temperature.The spectrum of the antenna measured from the tunneling transducer output appears in Figure 3.

The antenna has a band-width of 300 Hz centered around 950 Hz. This means that the energy transfer period between the bar and the end-mass is 3 msec. which sets the time resolution for determining the arrival time of an impulsive gravitational wave. This resolution should allow correlated detectors separated by a few thousand kilometers to obtain propagation delay and directional information about the gravitational waves.

If we extrapolate the results obtained with a prototype aluminum antenna to a silicon antenna with a fundamental mode of 1 kHz and a Q of 20 million at room temperature this translates into a noise temperature of 1.5 millikelvin. We have yet to demonstrate that a multimode silicon antenna can be made with a Q of 20 million however bare silicon bars of a few kilograms mass have been measured to have Q's in this range. A 150 kg silicon antenna with this noise temperature has a strain sensitivity $h = 6\times10^{-19}$. By cooling to liquid nitrogen temperature, and including the experimentally observed increase of the mechanical Q by a factor of 10, the strain sensitivity would become $h = 1.3 \times 10^{-19}$ which is comparable to the best multi-ton, liquid helium cooled aluminum antennae.

A crucial issue for gravitational wave detectors is the statistical nature of the noise. We have determined that the noise of the electron tunneling transducer is Gaussian to a reasonable approximation, see Figure 4. Occasionally the noise will have a much broader distribution than Gaussian but this seems to depend upon the specific treatment of the tunneling tip.



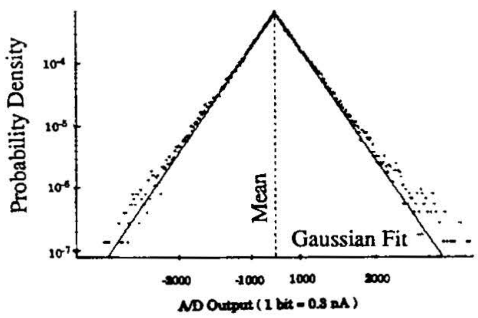


Figure 3 Frequency spectrum of 3-mode antenna with tunneling transducer.

Figure 4 Probability distribution of tunneling current innovation.

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4. References

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7. Private Communication - Silicon crystals of this size have been grown by Kayex-Hamco Corporation, Rochester, New York.