# VIII. GRAVITATION RESEARCH[*]

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## RESEARCH OBJECTIVES AND SUMMARY OF RESEARCH

The research in this group is in the field broadly labeled experimental relativity, in particular, experiments related to the gravitational interaction and measurable consequences of cosmological models.

### Specific Projects

### 1. Astronomy in the Region 1-0.1 mm

In this region of the electromagnetic spectrum there is some important astrophysics, such as the spectral peak of the alleged 2.7°K isotropic cosmic black-body radiation, thermal radiation by interstellar and possibly intergalactic dust, as well as intense radiation from galactic centers, and doubtless other information concerning the early history of an evolving universe.

An experiment carried out with a balloon-borne far infrared radiometer in the fall of 1969 indicated that the isotropic background radiation may not have a thermal spectrum and may be dominated by a strong line between 10 cm$^{-1}$ and 12 cm$^{-1}$. These results are tentative, since we were not able to vary several important parameters in the experiment. An improved radiometer is under construction which is scheduled to fly in the spring of 1971. Future flights will measure the spectrum of the isotropic background with a liquid helium-cooled lamellar grating interferometer that has 1 cm$^{-1}$ resolution. Measurements of the small- and large-scale spatial isotropy of the background radiation are planned.

### 2. Far Infrared Detection

(a) Development of low-noise InSb photoconductive detectors.

(b) Far infrared detection by parametric up-conversion in CdS pumped by the 5145 Å line of the Argon laser.

### 3. Test of the Strong Principle of Equivalence

An experiment to test the strong principle of equivalence and, in particular, to

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search for evidence of the Brans-Dicke scalar gravitational interaction which violates the strong principle has been studied by this group in conjunction with the Measurements Systems Laboratory of M. I. T. In this proposed experiment an atomic oscillator and a gravitational oscillator are both placed in a space probe; one measures the ratio of axis crossings of one oscillator relative to the other as the probe passes through varying gravitational potentials. Several gravitational oscillator configurations have been studied, one of which may be tested in Earth orbit in Skylab B.

4. Pulsar Gravitational Wave Antenna

5. Sensitive Intracavity Laser Polarization Interferometer

This may permit measurement of intrinsic laser phase noise.

R. Weiss

## A. MONOLITHIC CAPACITIVE GRID INTERFERENCE FILTERS FOR THE FAR INFRARED

For a balloon-borne liquid helium-cooled far infrared radiometer[1,2] we need low-pass filters with well-defined cutoff frequencies. Moreover, the filters have to be mechanically rugged and indifferent to repeated cycling between room and liquid-helium temperatures. The interference filters described by Ulrich[3] appeared to have optical properties that would meet our requirements, but they were mechanically unsuitable. His filters consist of multiple layers of "capacitive grids" or arrays of small metallic squares. The individual grids are formed on thin mylar films that are stretched over rings and separated by spacers. This method of construction insures flatness and parallelism of the reflecting surfaces, but the resulting filters are delicate and not suitable for cooling to low temperatures.

We have developed a method of construction which produces very rugged filters at the expense of some loss of control over the flatness and parallelism of the grids. Capacitive grids of silver are deposited on polyethylene substrates by evaporation, with wire screening placed flush against the polyethylene as masks. A 4-grid interference filter, for example, is assembled by fusing 5 layers of polyethylene (including one blank) together in a vacuum between heated pressure plates. A temperature of approximately 110°C and a pressure of roughly 3 $\text{lb/in.}^2$ applied for 15-30 min are adequate to fuse the individual components of a filter into a single piece. In order to avoid excessive flowing of the polyethylene it is important that the temperature be kept as low as possible in this step; hence, some experimention is required.

The spacing between the grids in a finished interference filter is determined by the thickness of the polyethylene substrate, which must be chosen appropriately. Ulrich[3] gives formulas by which the filter parameters, such as grid constants and the spacing between grids, may be selected. These formulas are for grids in vacuum; when the grids are embedded in a dielectric the filter parameters must be scaled by the index of refraction (~1.5 for polyethylene).

Several 4-grid filters, with nominal cutoff wave numbers of 6, 8, and 12 $cm^{-1}$, have been constructed. Figure VIII-1 shows the transmission spectra of two filters with 6 and 12 $cm^{-1}$ cutoffs, as measured with a Michelson interferometer. The grids for these filters were deposited on standard 0.012 in. and 0.006 in. polyethylene sheet. The screens used for masks had openings of 0.354 mm and 0.117 mm, wire diameters of 0.131 mm and 0.247 mm, and were cut from sieves No. 45 and No. 80 of the U.S. Standard Series. Grids in the same filter were oriented at random angles of 20-30° with respect to each other. The filters after trimming were 4.5 cm in diameter.

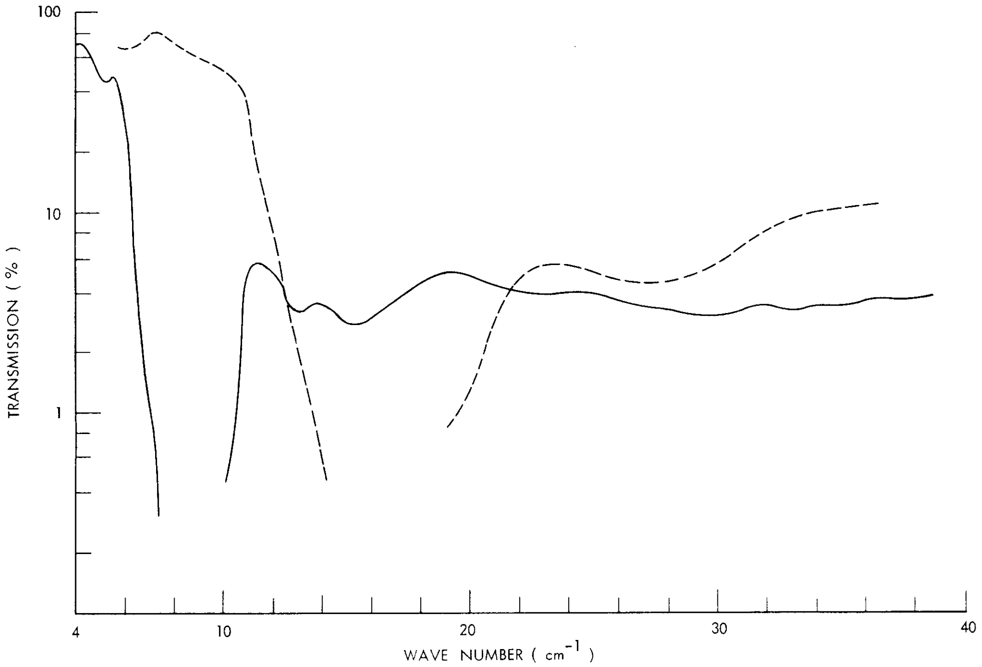

Fig. VIII-1. Transmission spectra of two lowpass interference filters.

In summary, we have found a method of making very rugged far infrared interference filters, suitable for cooling to liquid-helium temperatures. The ruggedness of the filters is illustrated by the fact that the three 12 $cm^{-1}$ filters that were used in the first balloon flights of our radiometer[1,2] survived a crash that otherwise completely destroyed the apparatus. The same filters will be used in future flights of a new apparatus.

D. J. Muehlner, R. Weiss

### References

1. D. Muehlner and R. Weiss, "Measurement of the Isotropic Background Radiation in the Far Infrared," Phys. Rev. Letters 24, 742 (1970).
2. D. J. Muehlner and R. Weiss, Quarterly Progress Report No. 96, Research Laboratory of Electronics, M.I.T., July 15, 1970, p. 61.
3. R. Ulrich, "Effective Low-Pass Filters for Far Infrared Frequencies," Infrared Phys. 7, 65 (1967).

## B. FAR INFRARED DETECTION BY PARAMETRIC UP-CONVERSION

In a classic paper on nonlinear optics Bloembergen[1, 2] proposed that a nonlinear dielectric medium could function as a parametric up-converter for infrared radiation. The scheme is shown in Fig. VIII-2, in which $\omega_1$ is the visible laser pump radiation, and $\omega_2$ the far infrared signal to be detected. The pump and signal wave generate nonlinear polarization waves in the material at many different frequencies; in particular, there is a time-dependent polarization at frequency $\omega_3 = \omega_1 + \omega_2$. If the polarization wave at $\omega_3$ has the same phase velocity as that of the traveling light wave at $\omega_3$ in the medium, the amplitude of the traveling wave may increase linearly with distance traveled in the medium. Depending on the amount of nonlinear polarization, as well as the precision of the velocity match, it is possible, in principle, to convert all photons at $\omega_2$ into photons at $\omega_3$ if there is sufficient pump power at $\omega_1$. The converted wave, $\omega_3$, is separated from the pump by high-resolution optical spectroscopy and detected by a photomultiplier.

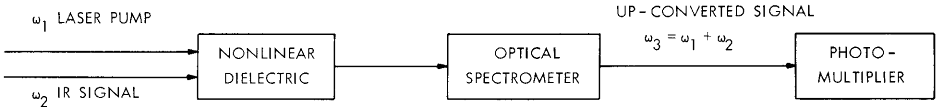

Fig. VIII-2. Parametric up-conversion scheme.

In principle, there is no intrinsic noise introduced into the signal by the up-conversion, since there should be no output at $\omega_3$ unless there is input at $\omega_2$ – there is no spontaneous emission noise. Thermal noise at $\omega_2$ is converted with the signal and can only be reduced by cooling the nonlinear dielectric, although it is not clear that the noise temperature of the dielectric is the lattice temperature. In the idealized case, it might be expected that the limiting noise is photomultiplier background that might limit the noise to a few photons/sec or a noise equivalent power at $\lambda_2 = 1$ mm of $\sim 10^{-21}$ W/Hz$^{1/2}$.

### 1. Some Equations Relating to Parametric Up-conversion

$\omega_1$ = visible pump.

$\omega_2$ = far infrared signal.

$\omega_3$ = up-converted sum signal.

The conversion efficiency is given by

$$\eta = \frac{\text{photons out at } \omega_3/\text{s}}{\text{photons in at } \omega_2/\text{s}} = \sin^2 \frac{\pi z}{\ell_{\text{int}}},$$

where

$$\left(\frac{1}{\ell_{\text{int}}}\right)^2 = \frac{16\,\pi^2\chi_{NL}^2 I_1}{c^3}\,\frac{\omega_2\omega_3}{n_2n_3},$$

with

$\chi_{NL}$ = magnitude of the nonlinear polarizability in esu

$I_1$ = visible pump intensity erg/s/cm$^2$

$n_2$ = index of refraction for $\omega_2$

$n_3$ = index of refraction for $\omega_3$

c = velocity of light cm/s

$\ell_{\text{int}}$ = twice the length in the medium over which there is complete conversion of $\omega_2 \rightarrow \omega_3$

z = the length over which there is a phase match.

The perfect phase-match condition for collinear waves is

$$k_3 = k_1 + k_2 \quad \text{or} \quad n_3\omega_3 = n_1\omega_1 + n_2\omega_2.$$

For imperfect phase matching there is a maximum length of medium, $z_{\max}$, such that the sum wave does not begin to feed energy into the polarization wave. This begins to occur when the two waves are $\pi$ phase apart.

$$z_{\max} \leqslant \frac{\pi}{k_3 - (k_1+k_2)}.$$

To give a typical example: Assume a cw Argon ion laser pump and a CdS crystal as nonlinear dielectric:

$\omega_1 = 3.6 \times 10^{15}$

$I_1 \sim 10^2 \text{ W/cm}^2$

$\chi_{NL} \sim 4 \times 10^{-7}$ cgs

$n_2 \approx n_3 \approx 2$

$\omega_2 \approx 2 \times 10^{12}$

$z_{max} \sim 1$ cm

$\eta = 2 \times 10^{-5}$

$\text{NEP}_{\text{at}} \lambda = 1 \text{ mm} \sim 10^{-17} \text{ W/Hz}^{1/2}$.

Several investigators have demonstrated that up-conversion from the near infrared is possible.[3-5] None have approached detection efficiency that even rivals conventional detectors, however. The principal difficulty is that since the nonlinear polarizability of most materials is small, a long phase-matched path is required in the material; however, the useful path lengths are limited by optical inhomogeneities. Several investigators[3,4,6] have used high-power pulsed lasers to achieve a conversion efficiency of as much as 1% in a small phase-matched path length. The duty cycle is only $10^{-6}$, however.

## 2. Specific Problems of Up-conversion in the Far Infrared

### (a) Separation of the pump from the up-converted signal

The relative frequency shift of up-converted light from the pump is small, for 1 mm radiation $\Delta\omega/\omega \sim 5 \times 10^{-4}$. To separate the pump from the signal requires high-resolution spectroscopy with little scattering. This is not a small problem when we consider that the pump beam may typically be $10^{18}$ photon/s, while the up-converted beam may include a few photons/s.

### (b) Scattering processes in the medium that contribute at $\omega_3$

Rayleigh scattering by inhomogeneities in the medium will be elastic, and should not convert $\omega_1 \to \omega_3$; however, Rayleigh scattering can scatter pump light from one polarization state into another. This may be troublesome if pump vs up-converted signal rejection is accomplished by giving these two waves orthogonal polarizations. This method can be used in a crystal with off-diagonal terms in the nonlinear polarizability tensor. Brillouin scattering is not a problem for up-conversion of radiation at 1 mm or shorter wavelengths. The relative frequency shift of an incident photon at $\omega_1$ that recoils at an angle $\theta$ after collision with a phonon is given for small $\theta$ by

$$\frac{\Delta\omega}{\omega} = \frac{v}{c} \sim 10^{-5}\,\theta,$$

where $v$ is the velocity of sound in the medium.

Raman scattering may be a problem; however, this depends on the nonlinear medium. Raman spectra in most materials are shifted by $\frac{\Delta\omega}{\omega} \sim 3 \times 10^{-2}$ from the pump.

### 3. Proposed Experiments

(a) Up-conversion in CdS using the 5145 Å line of the Argon ion laser as pump and a resonance absorption cell of molecular Iodine as a narrow-band absorption filter to eliminate the pump after the crystal

For collinear propagation, phase matching can be achieved by bi-refringence in CdS if the pump is propagated as the extraordinary ray and the far infrared signal, and the up-converted signal as ordinary rays. The experimental arrangement is shown in Fig. VIII-3.

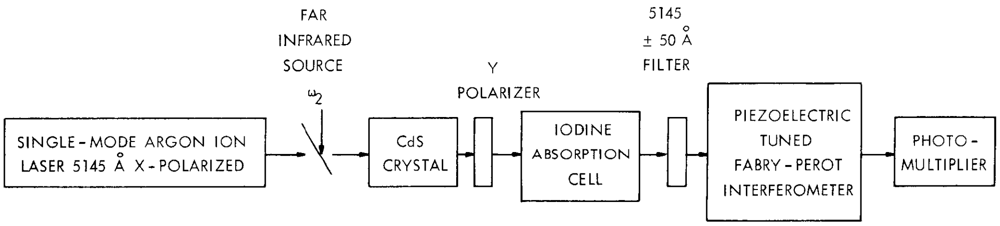

Fig. VIII-3. Experimental arrangement.

Pump rejection is achieved by (i) giving the pump wave orthogonal polarization to the up-converted wave, (ii) a narrow-band ($\Delta\omega/\omega \sim 10^{-5}$) absorption filter[8] of gaseous $I_2$, (iii) a bandpass transmission filter, 50 Å wide, at 5145 Å to eliminate the fluorescence of the $I_2$, and (iv) a piezoelectrically tunable Fabry-Perot spectrometer.

The nonlinear polarizability of CdS is not known at 5145 Å; at 6943 Å, $(\chi_{NL}) \sim 4 \times 10^{-7}$ esu.[3] The band gap of CdS at 300°K is ~5120 Å and, since the nonlinear polarizability becomes large near resonance, it may be an order of magnitude larger at

5145 Å than at 6943 Å. In the initial experiments the far infrared source will be an HCN laser operating at 337 μm.

(b) Phase matching and nonlinear polarizability in the region near anomalous dispersion in the mixing medium

It seems interesting to investigate the possibility that both phase matching and enhancement of the nonlinear polarizability can be achieved if the nonlinear medium is pumped in the region of anomalous dispersion. The frequency and phase conditions are

$$\omega_3 = \omega_1 + \omega_2 \qquad k_3 - (k_1+k_2) = 0 = n_3\omega_3 - (n_2\omega_2+n_1\omega_1)$$

$$(n_3-n_1)\omega_1 = (n_2-n_3)\omega_2.$$

Since $n_2$ and $n_3$ are very close

$$n_2 - n_3 = \left.\frac{\Delta n}{\Delta\omega}\right|_{\omega_2} \omega_1$$

$$(n_3-n_1) = \left.\frac{\Delta n}{\Delta\omega}\right|_{\omega_2} \omega_2$$

so that in a region of anomalous dispersion $\Delta n/\Delta\omega$ is sufficiently large to compensate for the difference in index for far infrared and optical radiation. The experiment can be tried in two ways, either by using different pump frequencies near $\omega_2$ or by varying the location of the anomalous dispersion by changing the temperature of the medium. For example, in CdS the band-gap wavelength changes from 5120 Å at 300°K to 4900 Å at 4°K.

R. Weiss

## References

1. J. A. Armstrong, N. Bloembergen, J. Ducuing, and P. S. Pershan, "Interactions between Light Waves in a Nonlinear Dielectric," Phys. Rev. 127, 1918 (1962).
2. N. Bloembergen, Nonlinear Optics (W. J. Benjamin, New York, 1965).
3. M. Takatsuji, "Theory of Far Infrared Detection Using Nonlinear Optical Mixing," Jap. J. Appl. Phys. 5, 389 (1966).
4. J. E. Midwinter and J. Warner, "Up-conversion of Near Infrared to Visible Radiation in Lithium-Meta-Niobate," J. Appl. Phys. 38, 519 (1967).
5. R. C. Miller and W. A. Nordland, "Conversion of Near Infrared to Visible Light by Optical Mixing," IEEE J. Quant. Elec., Vol. QE-3, p. 642, 1967.
6. J. Warner, "Photomultiplier Detection of 10.6 μ Radiation Using Optical Up-conversion in Proustite," Appl. Phys. Letters 12, 222 (1968).
7. G. D. Boyd, T. J. Bridges, and E. G. Burkhardt, "Up-conversion of 10.6 μ Radiation to the Visible and Second Harmonic Generation in HgS," IEEE J. Quant. Elec., Vol. QE-4, p. 515, 1968.
8. S. Ezekiel and R. Weiss, "Laser-Induced Fluorescence in a Molecular Beam of Iodine," Phys. Rev. Letters 20, 91 (1968).