INFRARED FIBER OPTIC FOCAL PLANE DISPERSERS

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SUMMARY

Middle and far infrared focal plane detectors are currently less inte-grated in their design than are those in the near infrared. The difficulties of low temperature processing steps on the ultrahigh purity germanium detector material, which is required in the far infrared, limit the realization of inte-grated circuit technology in the near future. As an alternative approach, we discuss the utilization of far infrared transmissive fiber optics as a compon-ent in the design of integrated far infrared focal plane array utilization. A tightly packed bundle of fibers is placed at the focal plane, where an array of infrared detectors would normally reside, and then fanned out in two or three dimensions to individual detectors. Subsequently, the detectors are multiplexied by cryogenic electronics for relay of the data.

A second possible application is frequency upconversion ($v_1 + v_2 = v_3$), which takes advantage of the non-linear optical index of refraction of certain infrared transmissive materials in fiber form. Again, a fiber bundle is uti-lized as above, but now a laser of frequency v_1 is mixed with the incoming radiation of frequency v_2 within the non-linear fiber material. The sum, v_3, is then detected by near infrared or visible detectors which are more sensi-tive than those available at v_2. Due to the geometrical size limitations of detectors such as photomultipliers, the focal-plane dispersal technique is advantageous for imaging upconversion.

INTRODUCTION

Currently, realizations of instruments based upon infrared upconversion are limited by the availability of large high quality non-linear crystals. I describe here how fiber bundles of the non-linear material can substantially eliminate the availability problem. Such "pixelized" crystals, i.e., the fiber bundles, can considerably increase the conversion quantum efficiency available at low pump power densities. The integration of optical components thru the use of fiber optics can considerably add to the ruggedness and usefulness of instruments based on their incorporation when compared with those utilizing discrete components.

DISCUSSION

Linear Fiber Optics

Infrared focal planes are now in a phase of extreme integration pressure. Users are not satisfied with a few good detectors which scan a scene to thereby construct a picture. Rather the availability of microcircuit technology has created a large demand for CCD or CID focal plane arrays which "pixelize" a scene with considerable facility and accuracy. The cost investment to produce custom arrays is considerable to the point of being prohibitive in many instances. Thus only a few standard array formats have become available, and those are in silicon for the visible and HgCdTe for the infrared.

In certain imaging applications the detector pixel size is not matched conveniently to the spatial resolution of the telescope. Several factors affect the spacial resolution; most notably they are "seeing", diffraction, and optical quality. Any of these can severely degrade the resolution so that several detectors measure several spatial resolution elements or vice versa. This results in a loss of information.

In Figure 1 we show a proposal for coupling dissimilar spatial resolution scales so that in effect they are equivalent. A conical fiber bundle of appropriate length is matched at one end to the spatial resolution scale of the focal plane and at the other end to the detector array scale. Note that if the detector size is much smaller than the resolution size, care must be exercised in the cone design so as not to totally retroreflect the light in the cone before it exits onto the detectors.

The scheme outlined in Figure 1 can be used advantageously in the visible, near IR, and middle IR, where integrated circuit technology produces suitable detector arrays. In the far IR, the silicon and HgCdTe detectors do not function. There are, so far, only germanium based detectors which are physically sizeable as well as discrete. In this case a solution is also possible using fiber optics of appropriate materials and is shown in Figure 2. Suitable fiber materials are KRS5 and AgBr. The cone is tied at the focal plane end, while the detector end is free as in a broom construction. Indi-

vidual detectors are then free to be placed over an appropriate spatial scale with due consideration to such ancillary components as integrating spheres, preamps, load resistors, and stressing clamp. It should be noted that fiber bundles are advantageous in space applications for routing focal plane images into compartments shielded from cosmic rays.

Nonlinear Fiber Optics

One of the really promising developments in optical materials in the last decade is the explosion of our knowledge about the properties and applications of non-linear optical crystals. Since non-linear properties were first investigated, it has been realized that one of their truly original applications is in the conversion of infrared radiation into visible where extremely sensitive detectors are available. There have been several success-ful instruments built for this purpose, but all suffer from one or another limitations imposed by the availability of pump sources or that of the requi-site non-linear material. It appears that some of these major problems can be alleviated through the introduction of non-linear fiber bundles as proposed here.

First I'll list the basic theoretical description of non-linear upcon-version. If photons of two different frequencies, v_1 and v_2 are simultaneously propogating thru a uniaxial crystal with an ordinary index of refraction n^0 and an extraordinary index n^e, then the crystal can be rotated to a specific angle θ_m, the mixing angle, such that the laws of conservation of energy and momentum for the waves can be simply related as

$$v_1 + v_2 = v_3 \quad \text{energy conservation}$$

and

$$\vec{k}_1 + \vec{k}_2 = \vec{k}_3 \quad \text{momentum conservation}$$

i.e., a third wave at v_3 is produced. Polarization must also be con-sidered and this leads to two types of momentum conservation or phase matching.

For Type 1 mixing both waves have the same ordinary polarization

$$n^0_1 v_1 + n^0_2 v_2 = n^e_3 v_3 \quad \text{Type 1}$$

For Type 2 phasematching, orthogonal polarizations are mixed

$$n^e_1 v_1 + n^0_2 v_2 = n^e_3 v_3$$

For uniaxial crystals, the polarization can be expanded in terms of the electric field strength E

$$P_i = 2 \sum_{i,j,k} d_{ijk} E_j E_k$$

The non-linear interaction is proportional to the product of field of strength of the two waves and the crystal's effectiveness as a non-linear medium is measured by d_{ijk}. Under certain assumptions about the symmetry of the polarization matrix, e.g., Kleinman symmetry, the experimental equivalent of d_{ijk} is d_{eff}. In practice it is almost impossible to evaluate d_{ijk} theoretically.

For an instrument, the practical parameter of interest is the quantum conversion efficiency η

$$\eta = \frac{512 \, \pi^5 \, d_{eff} \, I_L^2}{n_1 n_2 n_3 \, \lambda_2 \lambda_3 \, C} \left[\frac{\sin x}{x} \right]^2$$

where $x = \frac{(\Delta k l)}{2}$ and $\Delta k = | \vec{k}_3 - \vec{k}_1 - \vec{k}_2 |$

I_L is the laser pump intensity usually chosen at v_2 and l is the interaction length of the crystal. The term in brackets is related to the coherence length of the interaction X which is dimensionless. Of immediate practical interest are the important Manley-Rowe relationships which govern the power flow from wave to wave

$$\frac{\Delta P_1}{v_1} = \frac{\Delta P_2}{v_2} = \frac{\Delta P_3}{v_3}$$

which essentially state that 100% power conversion of infrared into visible photons is possible. Indeed that has been shown to be possible in the laboratory.

Instruments have been demonstrated based upon different non-linear crystals to produce infrared upconversion with respectable NEP's and η's. Boyd and Townes (1977) have used proustite ($Ag_3As\ S_3$) to make an astronomical imager with an NEP = 3×10^{-10} W/$\sqrt{Hz}$ and an $\eta = 2 \times 10^{-7}$. Images were obtained of the Sun, Moon, Mercury and VY CMa. Voronin et al (1975) used $AgGaS_2$ to achieve 40%=η with a high purity (α (1.06 μm) < 0.1 cm^{-1}) crystal able to utilize high laser energy levels. Note that η depends only on the pump power, not the signal source power. Hence the great interest in upconversion for low level signal detection. Gurski (1973) used a $LiIO_3$ crystal to convert 3.4 μm radiation with 100% efficiency. He also achieved an NEP = 1×10^{-15} W/$\sqrt{Hz}$. Both Voronin and Boyd were able to achieve imaging, as have other workers.

The requirements of high field strengths from the pump necessary to drive the non-linear interaction requires focusing the pump and signal source in the crystal to the threshold of damage, usualy at 10's of MW/cm^2 in presently available materials. Such high energies are usually available only from pulsed lasers of low duty cycle. This situation is a disadvantage in low level signal detection and leads to the apparently low n and NEP of Boyd and Townes.

From the expression for η, the easily controlled parameters of an up-converter are d_{eff}, I_L, and l. While η grows linearly with I_1, it grows as the square of d_{eff} and l. The search for materials with higher d_{eff} continues, but dramatic order of magnitude leaps are very unlikely. Present values of d_{eff} are limited to about 300×10^{-9} esu. Specific application may limit the useful d_{eff} to values less than 100×10^{-9} esu.

Refinement of material quality is more easily achieved than inventing new materials. Present absorption coefficients are usually greater than 0.1 cm^{-1}, limiting practical crystal usage to 10 cm lengths. However, because of the need to focus in crystals to up the field strength, the useful portion of crystal is in practice much less than this figure. The spectral bandpass Δv_{bp} of an upconverter is determined by the crystal length and is approximately $\Delta v_{bp} = l^{-1}$ in cm^{-1}.

In Figure 3, I propose that fiber bundles of non-linear material can be used to alleviate some of the above restrictions on the performance of infra-red upconverters. The fibers are able to maintain a given pump intensity I_L over greater lengths in a focused beam profile. The full length of a fiber can be employed usefully to increase n. If in the figure the collimated beams of v_1 and v_2 are focused on the crystal fiber bundle, then the image is preserved throughout the detection system. Longer lengths of fibers employed mean increased spectral resolution. Fiber bundles can also be formed from selected high quality lengths of fibers.

At the moment, the most promising material available for production of upconversion in fibers is $AgGaS_2$. Most all of its properties are known which are essential to production of such fibers. In a collaborative endeavor with R. Byer and R. Feigelson of Stanford University, D. Dimiduk, and myself, with the support of the Ames Research Center's Directors Discretionary Fund, are working to the realization of a fiber optical non-linear upconverter, with the goal in mind of achieving single photon counting in the 5-m region of the infrared with imaging capability.

REFERENCES

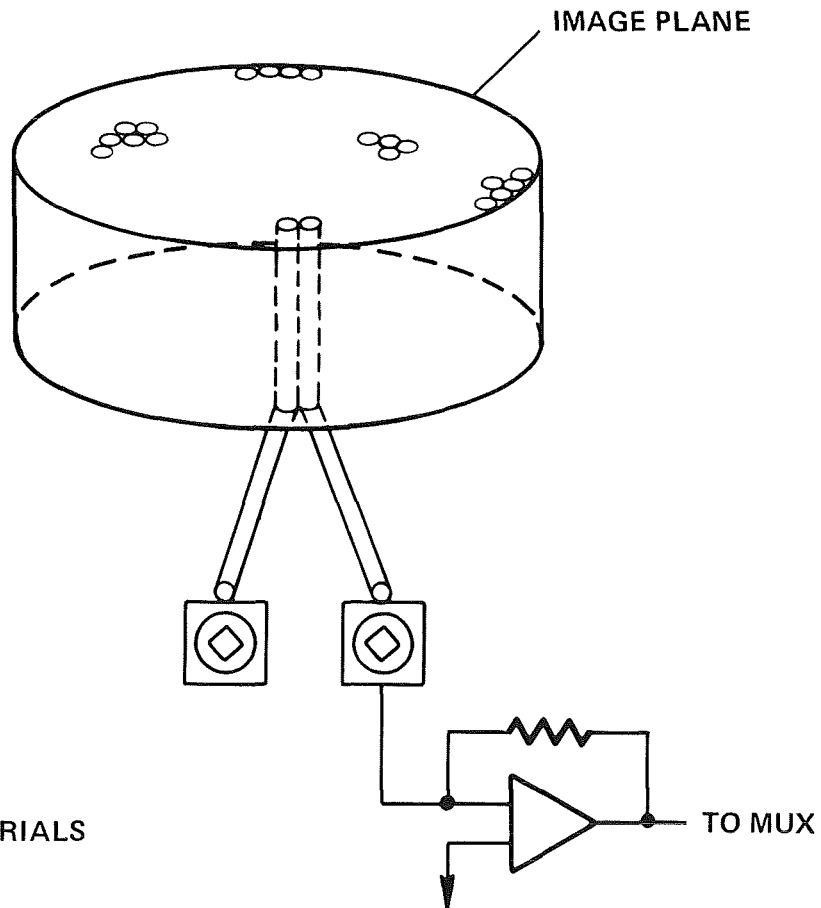Boyd, R. W. and Townes, C.H,. Applied Physics Letters 31, 440 (1977)

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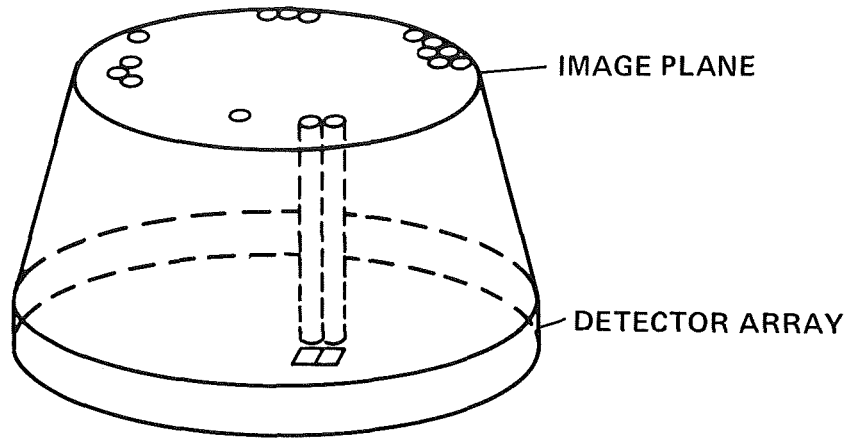
SUITABLE FOR
• GLASS FORMING MATERIALS

Figure 1.- Mid near IR imaging focal plane disperser.

SUITABLE FOR
• POLYMER MATERIALS
• CRYTASTALLINE MATERIALS

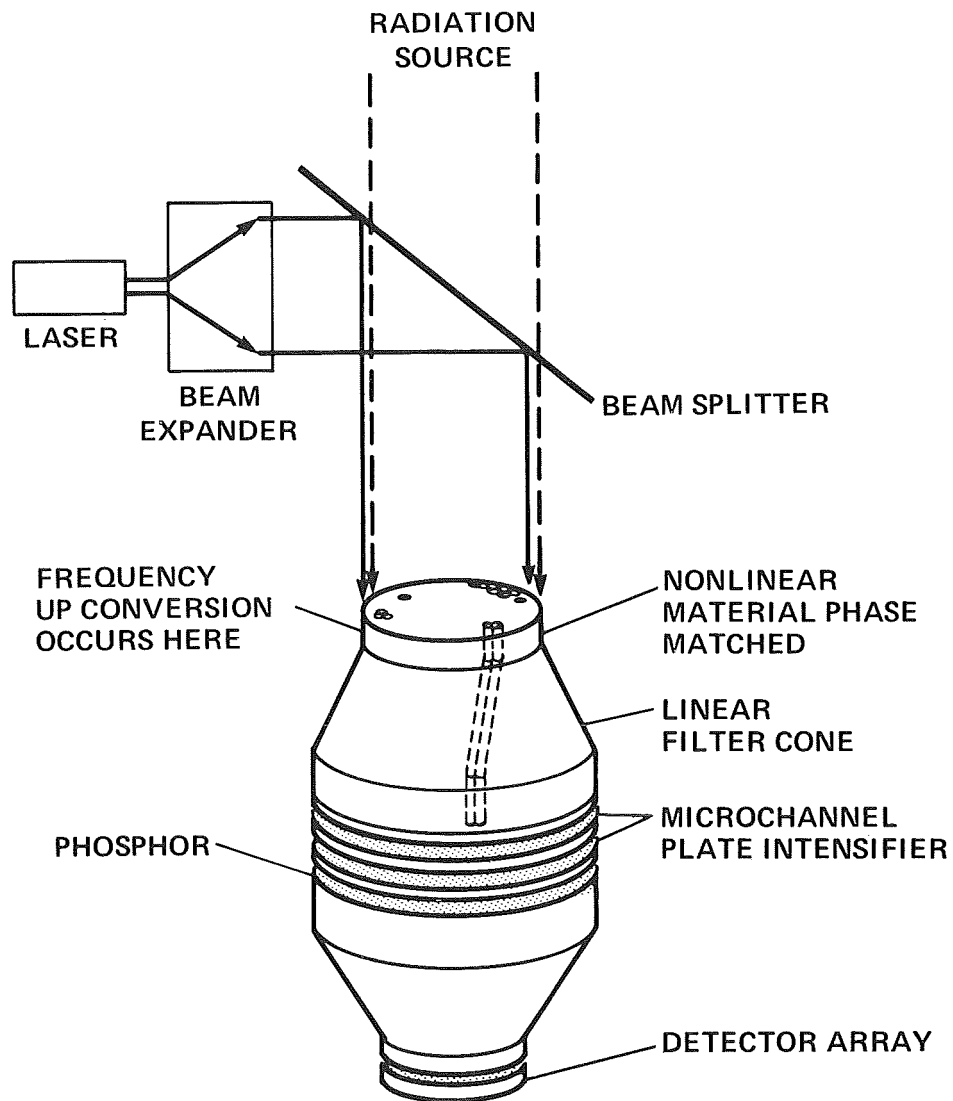Figure 2.- Far IR imaging fiber optic focal plane disperser.

Figure 3.- Mid IR focal plane disperser
used for imaging frequency upconversion.