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SUPERLATTICE GEOMETRY FOR GAMMA-RAY LASERS*

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ABSTRACT

The central problem to developing a graser--that pumping can inhibit or destroy the Mössbauer and Borrmann effects--can conceivably be mitigated by a superlattice geometry, into which collimated coherent transfer radiation is introduced to form a multiwave Borrmann (or antiBorrmann) mode. This could also overcome the limitations of cooperation length and Fresnel number that otherwise restrict the size and performance of a superradiant graser.

INTRODUCTION

Conceptual single-crystal grasers

Recent articles[1-3] have described hypothetical graser systems in which a nuclear population inversion is suddenly established by interlevel transfer from a long-lived isomeric state to another level in that nuclide, followed by a recoilless ("Mössbauer") gamma-ray transition. The graser body is a single-crystal host into which the active isomer has been incorporated substitutionally, so that wave modes can be established by Bragg-reflection that couple strongly to nuclear multipoles higher than electric dipole, but couple only weakly to atomic electrons.[2] It was shown in Reference 1 that, if the graser body is in the form of a cylinder or prism a few mm long with near-unity Fresnel number, doped with at least 10^{12} isomeric nuclei, superradiance[4] should evolve within a short time after the transfer step, hopefully before loss of crystal structure. To prevent premature dissolution of the graser crystal, however, the transfer process must be, not only rapid, but extremely efficient. We shall therefore assume herein that it will require a sharply tuned, monochromatic beam of coherent radiation,

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although we make no attempt here to identify a particular mechanism by which transfer is effected.

Wave modes of the gamma radiation

Bragg-reflection of gamma radiation in the primary lattice creates a superposition of Borrmann and anti-Borrmann modes.[5] Borrmann ("B") modes, having vanishing electric field amplitude at the lattice sites, interact only weakly with electric dipoles (atoms), but strongly with higher multipoles (most nuclei) near lattice sites; the converse is true for the anti-Borrmann ("A") mode. Coupling coefficients of B modes to various multipoles have been derived by Hutton, Hannon and Trammell.[6] The coupling coefficient of a B mode to an electric dipole contains as a factor the mean square displacement from the ideal lattice plane,[5] so that the B mode is absorbed only weakly by the atoms, but it can be amplified by "anomalous" stimulated emission[6] from magnetic dipole or higher multipolarity transitions in the nuclei; the A mode is strongly absorbed by atoms at lattice sites.[5] Exploiting the Borrmann effect greatly reduces the threshold excitation requirement and increases the lasing gain for a given level of excitation above threshold.[5] The several Bragg-reflected waves that interfere cooperatively within the crystal emerge as separated beams.

Limitations on graser performance

If the transfer pump is to illuminate the entire graser body simultaneously, the length of the graser cannot exceed the cooperation length for superradiance,[6] and its diameter is also limited by the Fresnel-number constraint; otherwise, the entire system will not emit as a coherent unit.[3] These two constraints on graser volume limit the intensity that can be generated. If, as well, the graser body is isolated, its temperature will rise rapidly, because of its small heat capacity, inhibiting the Mössbauer process.

However, the delivery of the transfer pulse and the attendant heating were not addressed in References 1-3. This paper enlarges upon an earlier proposal[2,8] for a way to increase the efficiency of the transfer step, thereby to reduce its heating effect, while avoiding restrictions on the energy that can be released coherently in superradiance.

THE SUPERLATTICE CONCEPT

Proposed geometry

Assume that the transfer radiation is an intense, coherent and well collimated electromagnetic wave of wavelength λ. It is proposed[8] to construct the graser by doping an extended host crystal with the storage isomer so as to form a two-dimensional lattice of linear regions (See Figure 1), each having dimensions typical of a single graser body. The transfer radiation, of wavelength Λ, is to be introduced as a multiple array of beams, each well collimated (as at the focal waist of a laser beam) at appropriate angles, to be specified below. Figure 2 illustrates four beams of transfer radiation incident at the Bragg angle upon the macroscopic superlattice.

Superlattice parameters

For definiteness, each of the active regions is assumed to be a long rectilinear parallelepiped, substitutionally doped with storage isomer, so that its internal crystal structure is a continuation of that of the undoped host, which, again for definiteness, is assumed to have simple cubic symmetry, the graser axes lying in the 110 direction. Let the lattice constant of the primary, host crystal be a; that of the two-dimensional array of doped ("graser") regions, d. Let the cross sections of the active regions be squares of side b. Assume that the doped regions have different scattering power and greater absorption than the intervening undoped regions of the host.

First, consider the relationship of d to a. Clearly, d will be an integer multiple of a (a large integer if Λ is an optical wavelength). In order that the several beams of transfer radiation entering the superlattice can interfere to establish a multiwave Bragg-reflected mode[6] with nearly the same cone angle and multiplicity as that of the gamma radiation to be stimulated in the primary lattice, the ratio a/d of primary-to-superlattice spacings should (approximately--subject to the integer constraint) equal that of graser-to-transfer wavelengths λ/Λ within the crystal. Transfer and gamma radiations then will have the same Bragg angles in their respective lattices and propagate parallel to the line of intersection of the reflecting planes at approximately equal velocities (except, of course, for dispersion). With swept excitation, the restriction of cooperation length[1] is avoided. Corresponding points in all active regions are pumped simultaneously, ensuring synchronism and, possibly, coherence among their respective output beams.

Wave modes of the transfer radiation

Figure 2 illustrates the directions and polarizations of four transfer beams. Table I shows the relationships of the external beams to the two principal wave modes they establish by Bragg reflections within the superlattice. For the B mode, the electric (but not the magnetic!) vector vanishes at each plane passing through the centers of doped (reflecting) regions. The electric vector of the conjugate, A mode is maximum at those planes. The Poynting vector $\underset{\sim}{S}$ is parallel to and either vanishing or maximum, respectively, at the axes of the doped regions.

Therefore, depending upon how the incident beams are phased, there are two possibilities for the transfer radiation within the superlattice.

Assume first that the transfer step requires a direct interaction with a nuclear magnetic dipole, electric quadrupole or higher multipole. The B mode of the transfer radiation, with enhanced nuclear but reduced electronic interaction, is the effective mode; vanishing of its Poynting flux mitigates heating in the doped regions. If it proves possible to control the relative phases of the paired beams of transfer radiation, no transition region containing the unwanted A mode will be present; otherwise, as in the gamma-ray case, the A mode will rapidly attenuate. Although the field amplitude in the undoped regions exceeds that in the doped regions, the increased coupling to the nuclear transition reduces the demand for transfer power and, therefore, further reduces the heating in the doped regions. The mean square extension of the doped material from the centers of the superlattice here corresponds to the negative logarithm of the Debye-Waller factor of the gamma-ray case.

Alternatively, suppose that the transfer process is indirect, first requiring an electric dipole interaction. For example, one postulated mechanism[8] for transfer involves exciting a collective dipole oscillation of the electronic shells that channels energy to the nucleus via a nonlinear near-field interaction.[9] The anti-Borrmann is then the preferred mode. In that case, wave interference increases the amplitude of the electric vector of the transfer radiation at the doped regions, and so, reduces both the power required of the transfer pulse and the heating in the undoped regions, facilitating their roles as heat sinks.

HEAT TRANSFER

Exact analysis of the thermal effect of the transfer pump in an actual graser superlattice awaits specification of the active and host materials, of the transfer radiation and its mode of interaction, of the cone angle and wave-mode multiplicity, absorption coefficients for both radiations in both doped and and undoped host, etc.

In the absence of such information, we consider a hypothetical case that illustrates the potential advantages of a superlattice geometry. The source regions are assumed to have the dimensions given in Table II and to be heated by absorption of the transfer flux given therein. Assume that the doped regions are the principal heat sources and neglect heat generation in the undoped regions of the host, which has the properties listed in Table II.

Assume that the cross sections of the active regions are squares of side $b \leq 0.1d$, with energy-absorption coefficient μ cm^{-1}. Let each of the four transfer beams be a square-wave pulse of power density P W cm^{-2}, lasting for Δt, and be incident at the Bragg angle θ. Assume further that the host is relatively transparent to the transfer radiation.

Then the heat deposited per unit length in each doped region of the superlattice is

$$Q_i = \Delta t \int_{-d/2}^{d/2} \int_{-d/2}^{d/2} \mu(x,y)\; S_i(x,y)\; dx\, dy \quad , \qquad i = A,B \tag{1}$$

approximately

$$Q_A = 4\; P\; \Delta t\; \mu\; \cos\,\theta\; b^2\left(2 - \frac{\pi^2 b^2}{6d^2}\right) \qquad \text{(A-mode)} \tag{2A}$$

and

$$Q_B = \frac{4\; P\; \Delta t\; \mu\; \cos\,\theta\; \pi^2 b^4}{6d^2} \qquad \text{(B-mode)} \tag{2B}$$

because the transverse dimensions of each source region are small compared with their separations.

To obtain an approximate value for the temperature dependence at specified points in the superlattice cell, we can therefore apply the well-known formula for the rise in temperature at a point $\underline{r}$ at the time t after a sudden generation of heat in an infinite line source located at $\underline{r}_0$,[10]

$$\Delta T = T_0\; \exp\left\{\frac{-|\underline{r} - \underline{r}_0|^2}{4\kappa t}\right\} \tag{3}$$

where

$$T_0 = \frac{Q}{4\pi\kappa C t} \tag{4}$$

κ = diffusivity

C = heat capacity per unit volume

in which κ is the diffusivity, c is the heat capacity per unit volume of the doped crystal.

Applied to an infinite two-dimensional square superlattice of line sources located at the points

$$x_0 = m\,d \quad , \quad y_0 = n\,d \quad ; \quad n,m = \ldots -2,-1,0,1,2\ldots, \tag{5}$$

this gives the formula

$$\Delta T = \frac{Q}{4\pi\kappa Ct} \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} \exp\left\{-\frac{(x - md)^2}{4\kappa t}\right\} \exp\left\{-\frac{(y - nd)^2}{4\kappa t}\right\} \tag{6}$$

which takes the special form

$$\Delta T\left(\frac{d}{2},\frac{d}{2}\right) = \frac{Q}{4\pi\kappa Ct} \exp\left\{-\frac{d^2}{8\kappa t}\right\} \sum_m \sum_n \exp\left\{-\frac{(m^2 + n^2)d^2}{4\kappa t}\right\} \tag{7}$$

at the cell centers (e.g., x,y = d/2) and

$$\Delta T(0,0) = \frac{Q}{4\pi\kappa Ct} \sum_m \sum_n \exp\left\{-\frac{(m^2 + n^2)d^2}{4\kappa t}\right\} \tag{8}$$

at the cell corners (e.g., x,y = 0, midlines of doped, active regions).

The indicated series converge rapidly and are readily evaluated on a small computer, using spreadsheet software. Figures 3 and 4 show results for the case of Table II.

COMMENTS

For parameters of the magnitudes assumed in the example, thermal relaxation to temperatures that allow the Mössbauer effect to recover before dissolution of the crystal[12] and loss of population inversion by decay is possible. Of course, these numbers may not be realistic, especially the neglect of host absorption. Alternatively, one can use this approximate calculation to establish limiting values for the system parameters.

This demonstrates that a superlattice geometry could have the following advantages:

1) reducing the intensity of the transfer source that is needed for a given transfer rate;

2) providing a heat sink;

3) circumventing restrictions on the amount of graser material that would otherwise be imposed by the requirements of coherence.

This example has treated a four-wave case for simplicity. A still simpler, more easily constructed geometry, using a layered host and ordinary two-wave Bragg reflections, would also have some advantage. Higher multiplicity would give even greater advantages in reducing transfer and increasing output requirements and is, of course, possible. For example, Hutton has pointed out that a six-beam wave mode can couple well to electric octupole transitions.[6] Introduction of any number of beams of transfer radiation at a common cone angle can be accomplished by means of a conical lens[13] or mirror; the transfer radiation pulse will advance along the graser axis as a traveling-wave.

However, strict collimation, monochromaticity, coherence, and low host absorption of the transfer radiation are essential. The possibility of preparing such a structure will depend strongly on the physical, chemical and crystallographic properties of the host and dopant as well as the nuclear properties.

The effect of interactions among the various regions on the kinetics and coherence of the superradiant emission from the superlattice system requires further study.

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*Work supported by IST/SDIO and administered by NRL.

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FIGURES

1. Proposed superlattice geometry for gamma-ray lasers: a large single-crystal host in which the active material is disposed in a regular array of linear regions, forming a set of parallel graser bodies, each of unity Fresnel number. In this case, a square array is depicted; other geometries (e.g., hexagonal) are possible.

2. Diagram illustrating the introduction of four beams of transfer radiation incident at the Bragg angle on a graser superlattice. Propagation ($\underline{k}_i$) and polarization ($\underline{E}_i$) vectors are indicated.

3. Temperature rise at the graser regions and at the center of a superlattice cell, as a function of time after a transfer pulse in a Borrmann mode, calculated using the data of Table II and Equation 6.

4. Temperature rise at the graser regions and at the center of a superlattice cell, as a function of time after a transfer pulse in an antiBorrmann mode, calculated using the data of Table II and Equation 6.

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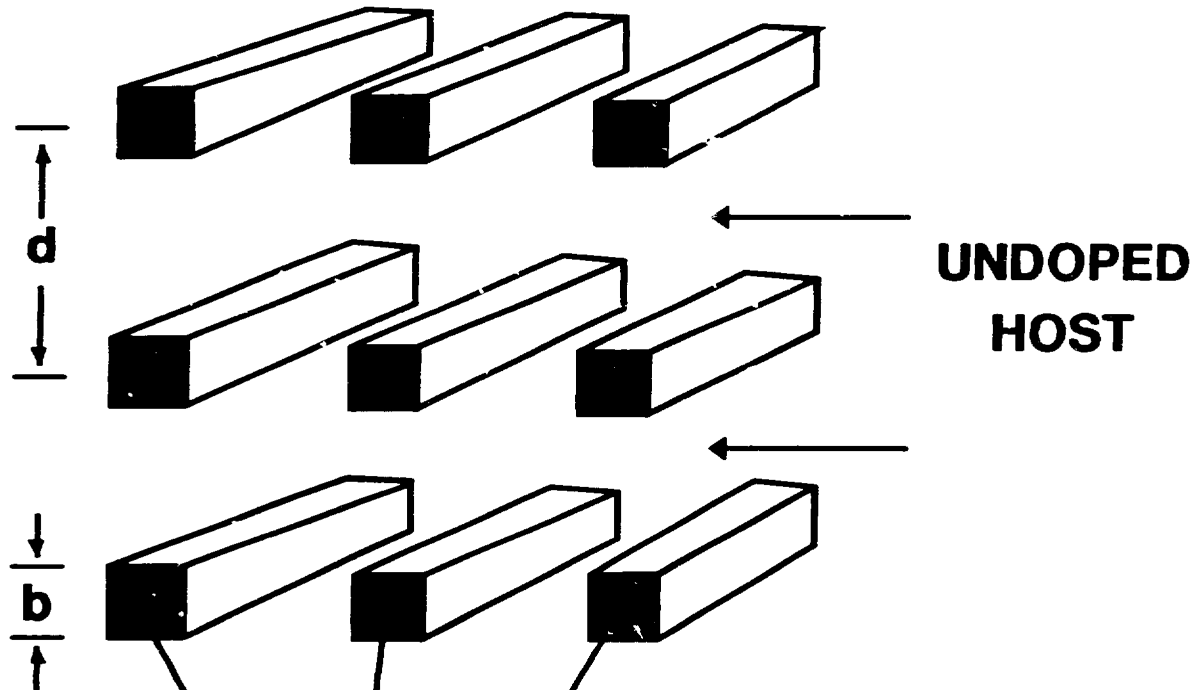
GRASER SUPERLATTICE



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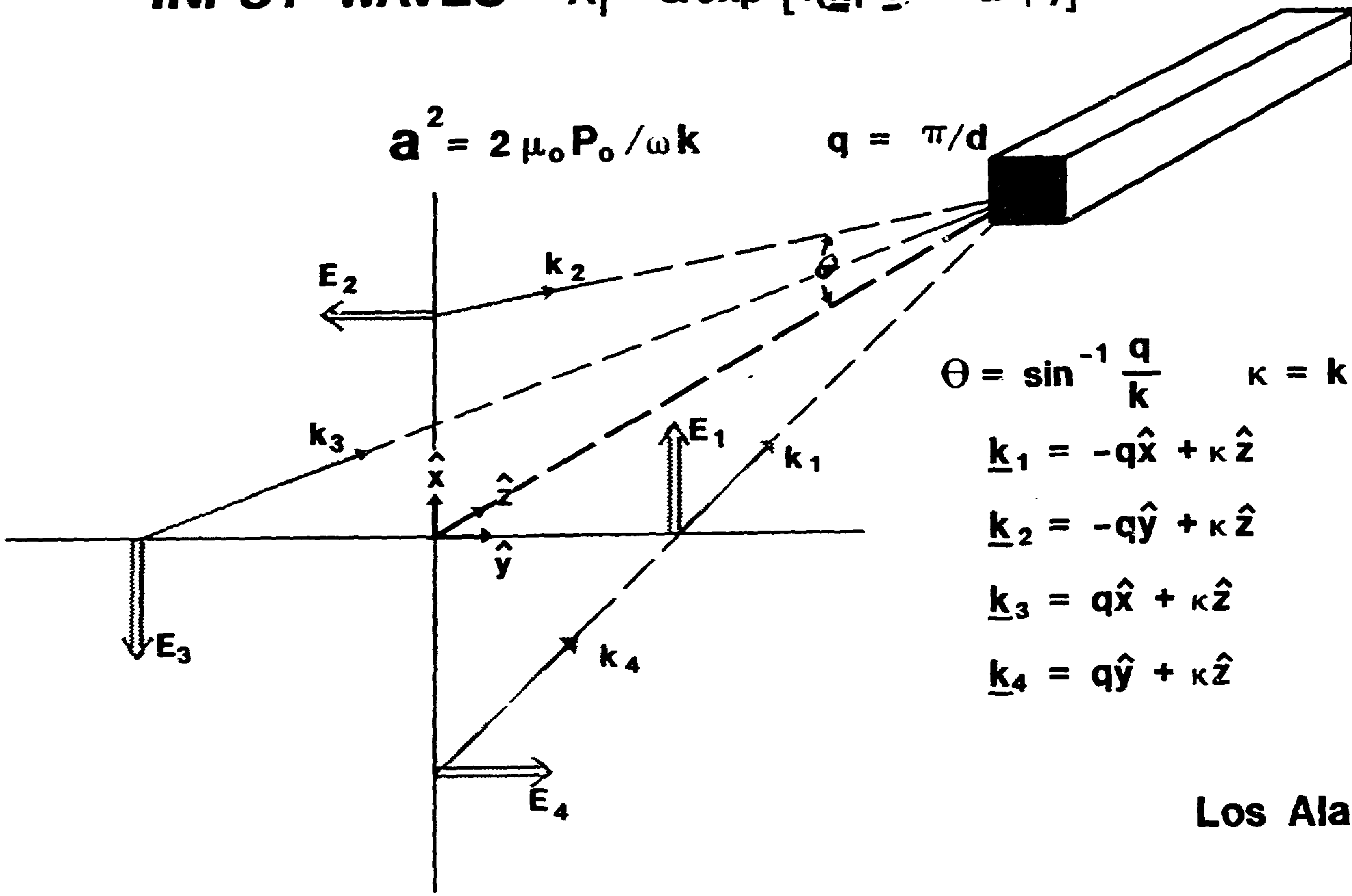
INPUT WAVES $A_i = a \exp\{i(\underline{k}_i \cdot \underline{r} - wt \pm \varphi)\}$

$$a^2 = 2\mu_o P_o / \omega k \qquad q = \pi/d$$



$$\Theta = \sin^{-1}\frac{q}{k} \qquad \kappa = k\cos\Theta$$

$$\underline{k}_1 = -q\hat{x} + \kappa\hat{z}$$

$$\underline{k}_2 = -q\hat{y} + \kappa\hat{z}$$

$$\underline{k}_3 = q\hat{x} + \kappa\hat{z}$$

$$\underline{k}_4 = q\hat{y} + \kappa\hat{z}$$

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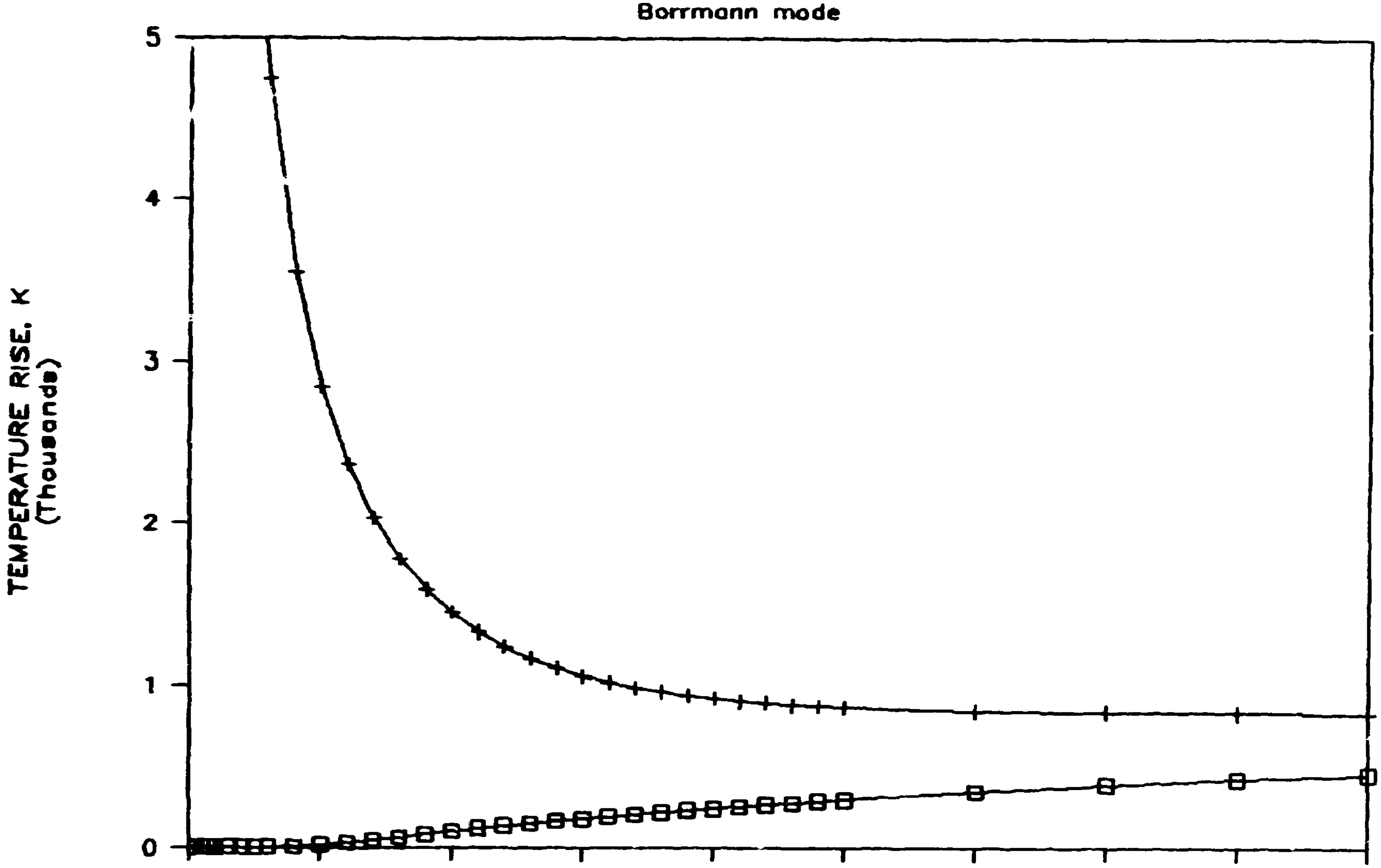
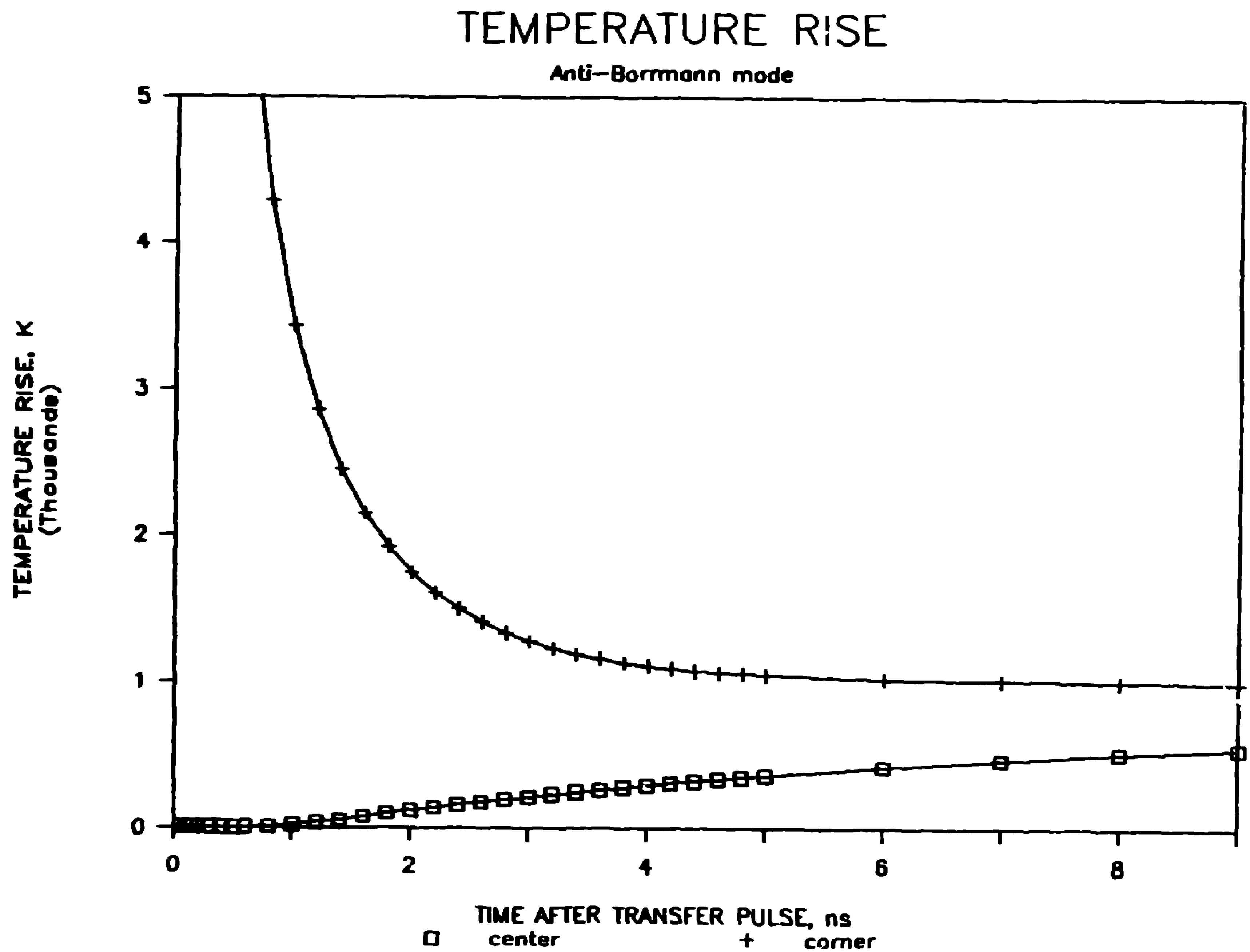
TEMPERATURE RISE




TEMPERATURE RISE
Anti-Borrmann mode
TEMPERATURE RISE, K
(Thousands)
5
4
3
2
1
0
0
2
4
6
8
TIME AFTER TRANSFER PULSE, ns
center
corner

TABLES

I. Relationships of externally incident waves of transfer radiation to the internal wave modes created by four-wave Bragg reflections within a square superlattice.

2. Numerical values of the system's parameters that were assumed for the numerical example on which Figures 3 and 4 are based.

INTERNAL WAVE MODES

$$q = \frac{\pi}{d} = k \sin\theta \quad \kappa = k \cos\theta$$

	FIELD	AMPLITUDE	WAVEFACTOR	ANTI-BORRMANN	BORRMANN
ELECTRIC	E_x	$2i\omega a$	$\exp\{i(\kappa z-\omega t)\}$	$-\cos qy$	$-\sin qy$
	E_y	$2i\omega a$		$\cos qx$	$\sin qx$
	E_z	0			
MAGNETIC	B_x	$2i\kappa a$		$\cos qx$	$\sin qx$
	B_y	$2i\kappa a$		$-\cos qy$	$-\sin qy$
	B_z	$2qa$		$-\sin qx - \sin qy$	$\cos qx + \cos qy$
POWER	S_z	$4P_0 \cos\theta$		$\cos^2 qx + \cos^2 qy$	$\sin^2 qx + \sin^2 qy$

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TABLE II

CALCULATION OF TEMPERATURE RISE IN A SUPERLATTICE

SUPERLATTICE PARAMETERS

θ	45.0	degrees	Bragg angle of primary gamma radiation
n	8	-	Order of Bragg reflection, transfer radiation
Λ	248.0	nm	Wavelength of transfer radiation
d	1.40E-06	cm	Spacing of the doped regions (superlattice)
b	1.40E-07	cm	Width of the doped regions

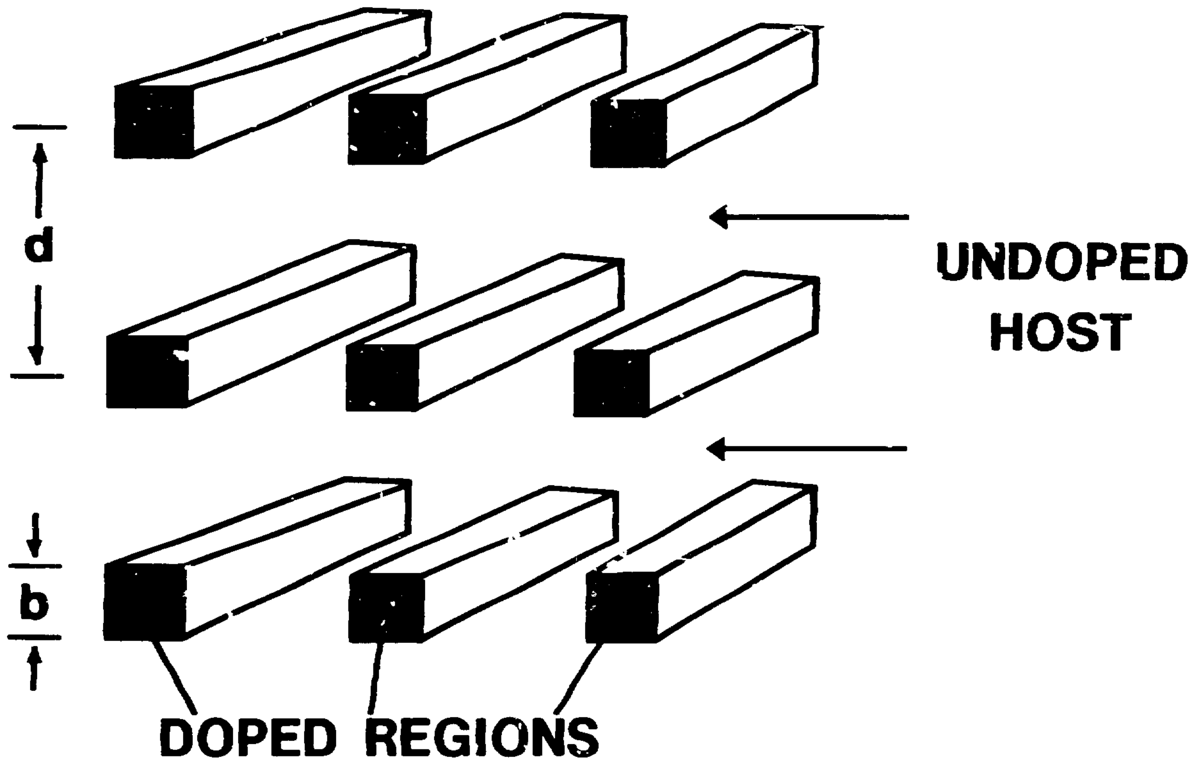
THERMAL PARAMETERS

κ	0.460	sq.cm/s	Thermal diffusivity of host
μ	5.000	per cm	Energy absorption coefficient of dopant
C	0.666	cal/sq.cm*K	Thermal capacity of unit volume of host

TRANSFER PULSE PARAMETERS

	A-MODE	*B-MODE*	
	1.9836	0.0164	Mode factor
Δt	1.000E-12	1.00E-12	Duration of transfer pulse, s
P	1.000E+16	1.00E+18	Power flux of each transfer beam, W/sq.sm
Q	5.52E-05	4.58E-05	Heat created per unit length of dopant,J/cm

GRASER SUPERLATTICE



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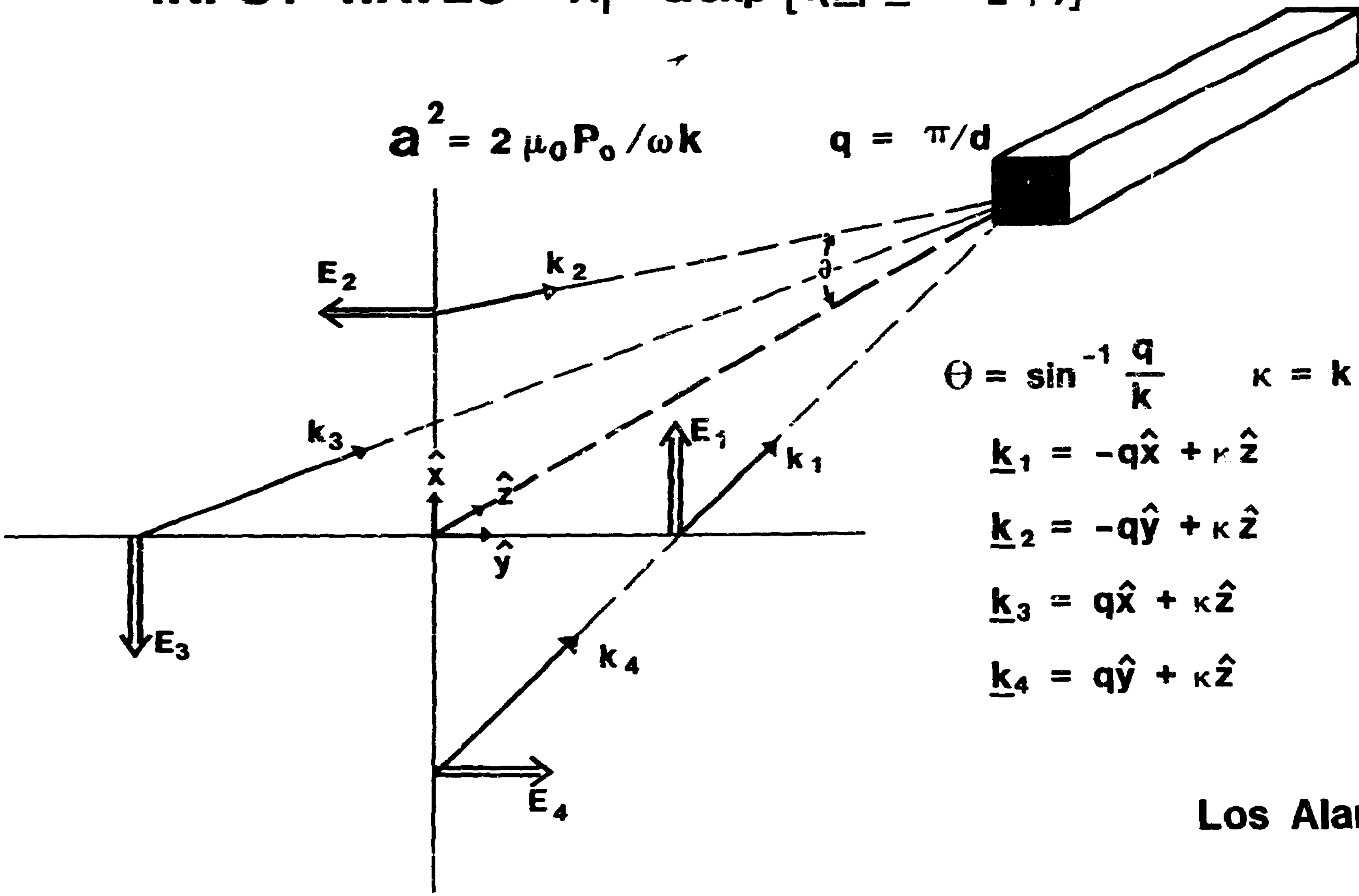

$$\Theta = \sin^{-1}\frac{q}{k} \qquad \kappa = k\cos\Theta$$

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