Physics of optical switching

R. L. Fork
Bell Telephone Laboratories, Holmdel, New Jersey 07733
(Received 17 November 1978; revised manuscript received 16 April 1982)

Relatively fundamental problems in physics hinder realization of the potentially large information-handling capability offered by optical switching. This paper examines the physics of optical switching in a way which exhibits those problems and which suggests strategies for their solution. The primary limits on optical switches arise from heat generated during the switching process. The principal barriers to easing those limits are the small value of interaction cross sections for atoms in solid-state materials and the lack of high-finesse microresonators for the optical field. The research most relevant to the solution of these problems appears to be that dealing with enhanced atom—optical-field interactions in solid-state microstructures. Short-optical-pulse generation and the short-time dynamics of solid-state microstructures are also highly relevant.

I. INTRODUCTION

Optical switching offers very powerful information handling capabilities; however, realization of those capabilities is hampered by fundamental physical problems. We examine optical switching in a way which exhibits those problems and which suggests strategies for their solution. We find, for example, that a deeper understanding of atom—optical-field interactions in solid-state microstructures is of special interest. We also find earlier analyses of optical switching[1,2] more pessimistic than necessary. Finally, we observe that recent work on transient phenomena in solid-state materials,[3,4] short-optical-pulse generation,[5] and enhanced optical interactions in solid-state microstructures[6,7] evidences progress toward the goals identified here.

The most closely related previous work is a paper by Keyes and Armstrong,[1] later developed further by Keyes.[2] We differ from these authors principally in that we arrive at more optimistic conclusions concerning the capabilities of optical switching systems. There are several reasons for this difference. (1) We disagree with the assumption of Keyes *et al.* that it is necessary that a quantum of optical energy be dissipated in an optical switch for each cycled atom. Rather we suggest that a significant fraction of the switching energy can be dissipated external to the switch. (2) We include the role of a resonator and show that proper use of a resonator can reduce switching energy without necessarily reducing bandwidth. (3) We find that cooperative phenomena in solid-state materials can be used to obtain significant reductions in switching energy over the case where atoms act independently. (4) We observe, that as switching rates approach optical frequencies, 10^{12} to $10^{14}\,\mathrm{sec}^{-1}$, other types of switches simply cannot compete at all.

Finally, we do agree with Keyes *et al.* that serious problems continue to hinder realization of the large potential offered by optical switching systems. We also suggest, however, that strategies exist for attacking those problems.

A considerable body of literature on optical switching extends back to times shortly after discovery of the laser. A review of early attempts to realize optical computers is given by Tippett *et al.*[8] Bistable operation and hysteresis in a laser oscillator was realized at an early stage.[9] More recent efforts have emphasized bistable transmitting elements.[10] Very recent work has demonstrated what is perhaps the most powerful advantage of optical devices, namely, the capacity to generate extremely short pulses ($\sim$30-fsec duration).[5]

It is important to recognize at the outset that serious limitations make it difficult to construct optical switching systems which approach the fundamental limits examined here. Summarizing briefly the findings of the paper we find the two primary limitations are (1) the cross sections of individual atom transitions providing gain in solid-state materials typically depart from their optimum values by very large margins [e.g., ~ 10 orders of magnitude for the Nd^{3+} 1.06-μ transition in yttrium aluminum garnet (YAG)]. (2) Optical resonators of high finesse with optical wavelength dimensions are difficult to fabricate.

The origin of these problems is quite fundamental. For example, the reason for the large departure of atomic cross sections in solid-state materials from their maximum theoretical value is that the close proximity of other ions causes severe line broadening unless both excited and ground states belong to an inner shell (e.g., $4f^n$) configuration; however, in the latter case the transitions are parity forbidden and hence have small oscillator strengths. Thus, the change which decreases broadening also decreases oscillator strength so that, in either case, realizable cross sections are small compared to the theoretical maximum.

The problem of obtaining high-finesse resonators of optical wavelength dimensions also has a fundamental character. That is, metals are lossy at optical frequencies (utilizing superconducting materials is not a practical solution since the existing energy gaps are all small compared to optical frequencies), and the use of multiple layers of dielectric material is not easily extrapolated to resonators of optical wavelength dimensions.

The key problem of reducing the energy dissipated in the switch is, in large part, the same as the problem of realizing large cross sections and resonators of high finesse with optical wavelength dimensions. That is, the most straightforward way of decreasing the energy dissipated in the switch is to use fewer cycled atoms and minimize absorption losses. These goals, however, reduce again to a need for large atomic cross sections and high-finesse resonators. Resolutions to these problems appear to lie primarily in use of cooperative phenomena in solid-state microstructures as discussed in Sec. IX.

II. SWITCHING COMPONENTS

The problem of optical switching is, in essence, the problem of utilizing one optical pulse to control a second optical pulse by virtue of their interaction with a common atomic system. The physical properties of interest are thus the rate at which energy can be transferred between an atomic medium and the pulse, and the thermal energy which is left in the switch as a result of that process. We examine ways of maximizing the transfer rate between atomic system and optical pulse while minimizing the heat left in the switch as a result of that transfer. In the following, we define components, properties, functions, and capabilities necessary to a discussion of these problems.

An optical pulse is any pulse in the optical frequency range which propagates in the switch or optical guides, or both. This definition is general, so as to include excitations which are not well approximated as pure photon states. While the possibility of using excitations with more complex dispersion curves is recognized, the linear dispersion relation

$$\nu\lambda = v \tag{2.1}$$

is assumed to hold unless otherwise specified. The frequency distribution of the optical pulses is assumed to be a normalized Lorentzian function [see (5.2) below]. We use $\Delta\nu_p$ as the pulse bandwidth and it is related to the pulse duration τ_p by

$$\Delta\nu_p = \frac{1}{2\pi\tau_p} \ . \tag{2.2}$$

Finally, *the pulse which causes a switching event is the switching pulse, and the pulse which is altered as a consequence of the switching event is the switched pulse.*

The atomic system is a collection of identical atoms which exhibit a significant interaction with optical pulses. The phrase significant interaction means here that the product of the absorption or gain coefficient (averaged over the optical pulse bandwidth) $\bar{\alpha}$ and the mean propagation distance $\bar{l}$ of the optical pulses in the interaction region, is at least unity for the case of resonant interactions, or that the phase shift experienced by the optical pulses on propagating a distance $\bar{l}$, averaged over the pulse bandwidth, is at least one radian for the case of nonresonant interactions. The atoms are treated as stationary and, unless otherwise specified, are assumed to behave independently[11] in their interaction with light. *The number of cycled atoms is the number of atoms in the atomic system which are caused to make an optical transition and return to their original state in a switching operation and is denoted by N_c.*

Four classes of atoms, having the energy levels shown in Fig. 1, are used in this discussion. The classes of principal concern are those exhibiting transient changes of state. These are shown in Figs. 1(a)–1(c) and produce gain [Fig. 1(a)], absorption [Fig. 1(b)], or a refractive index change [Fig. 1(c)] at the frequency of the switched pulse ν_0. The optical transition moment, linewidth, frequency, and population difference for a transition from level i to level j are denoted by μ_{ij}, $\Delta\nu_{ij}$, and N_{ij}, respectively, where i and j can take on any of the values indicated in Fig. 1. It is assumed that the transitions connecting levels 1 and 3, and 1 and 2 are radiative and that the transitions between levels 2 and 3 are nonradiative. (This situation is almost invariably required in any optical element providing useful gain.) A class of atoms which can exhibit semipermanent changes are also included [Fig. 1(d)].[12] The atomic

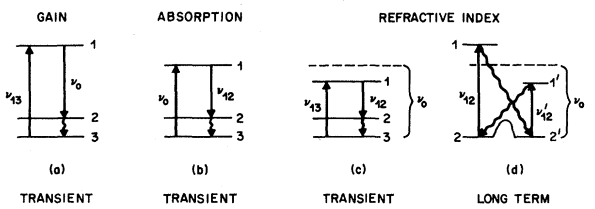

FIG. 1. Types of atomic systems. (a) Gain system. Levels 1 and 2 exhibit a population inversion in the absence of a saturating field with peak gain at $\nu=\nu_0$. Level 2 relaxes nonradiatively to the ground state at a rate $\gamma_{23}\gtrsim\gamma_w$. (b) Absorption system. Levels have a thermal population distribution in the absence of a saturating field with peak absorption at $\nu=\nu_0$. (c) Transient refractive-index system. Transition frequency ν_{13} between 1 and 3 is defined to be greater than or less than ν_0 by an amount greater than the transition linewidth. (d) Reversible bistable refractive-index system in which a write pulse at ν_{12}, or erase pulse at ν'_{12} ($\nu_{12},\nu'_{12}\neq\nu_0$) cause semipermanent changes in the refractive index at ν_0.

density is denoted by ρ.

The resonator is an element which confines the optical pulses (Fig. 2). For the purpose of this discussion, the resonator will be taken as having no absorptive losses, unless otherwise specified, and as being composed of a pair of plane parallel reflectors of reflectivity r. The *resonator finesse* is

$$F=\frac{\pi\sqrt{r}}{1-r}\ . \tag{2.3}$$

It will, in general. be assumed that $r\cong 1$, so that $\sqrt{r}$ can be approximated by unity. The resonator length is l_w. It is assumed that the optical fields are confined within a region of uniform cross section extending along the resonator axis. This cross section is a_w.

Efficient switching will, in general, require that the resonator loss rate not be slow compared to the rate at which energy is transferred between the atomic system and the optical fields. While violation of this condition can be tolerated to a modest extent, and is required for the laser oscillator action which is essential to the model switch (Sec. VIII), an upper limit is imposed on the resonator finesse by requiring

$$F=\frac{\pi v}{l_w\gamma_w}\xi\ , \tag{2.4}$$

where γ_w is the switching rate and ξ is an adjustable parameter, which can be larger than, but not very large compared to one. The mean propagation distance for light in the resonator is $\bar{l}$:

$$\bar{l}=\left[1+\frac{F}{\pi}\right]l_w\ . \tag{2.5}$$

A switching element is an atomic system and the resonator, or resonators, containing the atomic system. An optical switch is a set of optical switching elements, which may be one or more in number, which enable one optical pulse (the switching pulse) to cause a significant change in the behavior or properties of a second optical pulse (the switched pulse).

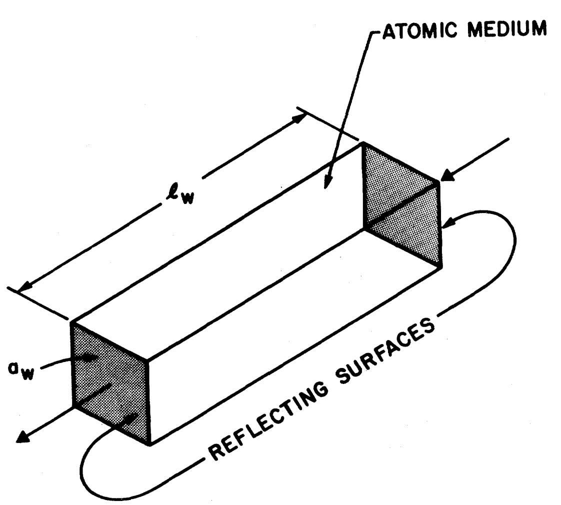

FIG. 2. Switching element. A resonator of finesse F with reflectors spaced by l_w confining optical pulses in a cross section of area a_w and containing an atomic system.

III. SWITCH PROPERTIES

We define the properties of the switching elements as follows: *The switching element dimensions are the same as those of the region occupied by the optical fields.* Thus, the switching element has a length l_w and a cross section a_w (see Fig. 2). The limitations placed on l_w and a_w are

$$l_w\geq\lambda\ , \tag{3.1}$$

$$a_w\geq\lambda^2\ . \tag{3.2}$$

The switching element volume is v_w and is limited to values

$$v_w\geq\lambda^3\ . \tag{3.3}$$

A *switching event is a causal change in the product $\bar{\alpha}(\nu)\bar{l}$ of at least a factor of 2 for the case of resonant interactions, or a causal change in the phase shift of an optical pulse* while propagating a mean propagation distance $\bar{l}$ of at least a factor of 2, followed by a restoration of the switching element to its original state. The word, causal, excludes purely spontaneous changes, such as relaxation of a group of atoms via spontaneous emission or superfluorescence.

We have chosen a small change in $\bar{\alpha}(\nu)\bar{l}$ in this definition so as to obtain a measure of the performance which might be obtained in an ideal switch. In actual switches a larger change will typically be required. In particular, in comparing our results with those of Keyes[1,2] it should be recognized that Keyes requires changes in $\bar{\alpha}(\nu)\bar{l}$ very large compared to one so as to achieve reliable switching.

It is desirable to have a measure of the capacity of the switching to enable a weaker pulse to control a stronger pulse. Thus, the *switching gain G is the ratio of the number of quanta in the switched pulse to the number of quanta in the switching pulse.* The switching gain is always positive and has the same value whether the switched pulse is transmitted or not.

The switching rate γ_w is the rate at which energy is transferred to the optical fields from the atomic system, or vice versa. In the following, the resonator relaxation rate is set equal to the switching rate [i.e., ξ is taken as 1 in Eq. (2.4)] unless otherwise specified. The duty cycle at which the switches are operated is η.

IV. SWITCH CAPABILITIES

Switching systems, in general, require directivity, isolation, gain, quantization, nonlinear behavior, memory, reliability, and a capacity to execute the basic switching functions.[13] Optical switching systems will presumably also require these capabilities. Some of the special advantages enjoyed by optical systems are the capacity to propagate signals at the maximum possible velocity and to execute operations at rates approaching optical frequencies. Some of the special problems associated with optical systems are the spontaneous emission noise which necessarily accompanies optical gain, the lower limit of an optical wavelength placed on most dimensions, and the need to work with minimum quantum energies $h\nu$ large compared to kT.

The weak nature of the photon-photon interaction appears to be an advantage as regards isolation of one optical pulse from another. That is, the problems of inductive and capacitive coupling, which become severe in very small electronic circuits, are avoided; however, coupling via scattering and evanescent wave leakage must be considered.

The problem of realizing useful optical switching usually reduces to realizing the capabilities listed at the beginnning of this section in a way which minimizes the required energy, time, and space. That problem in turn reduces, in large part, to transferring energy between an atomic system and an optical pulse in a way which is highly predictable and minimizes the required energy, time, and space. While minimizing transfer time usually means increasing the expenditure of energy, reducing the volume of the switch usually aids in reducing both the switching time and required energy. We thus expect a strong tendency for the dimensions of the most efficient optical switches to approach optical wavelengths.

V. OPTIMAL SWITCHING ELEMENTS

We examine here the problems of maximizing the switching rate and minimizing the heat dissipated in a switch. The minimum number of atoms which must be cycled per switching event N_c is calculated by writing the gain coefficient for the case of N atoms in state 1, and no atoms in state 2 [Fig. 1 (a)]. The parameter N_c determines the minimum energy which must be dissipated in the switch, and hence, eventually, the capacity of the system as a whole. The gain coefficient is[14]

$$\alpha(\nu)=\frac{N_1}{4\pi^2 v}\frac{\lambda^3 \nu\gamma_s}{v_w \Delta\nu_0}L(\nu)\ . \tag{5.1}$$

The function

$$L(\nu)=\frac{\Delta\nu_0^2}{(\Delta\nu_0)^2+4(\nu-\nu_0)^2} \tag{5.2}$$

is a normalized Lorentzian. Here, γ_s denotes the spontaneous relaxation rate in a vacuum, $\Delta\nu_0$ denotes the linewidth of the transition in the absence of saturation, and the statistical weights of upper and lower states are taken to be equal.

Integrating over the gain bandwidth gives an average gain

$$\bar{\alpha}=\frac{N_1}{4\pi^2 v}\frac{\lambda^3}{v_w}\frac{\nu\gamma_s}{(\Delta\nu_0+\Delta\nu_p)}\ . \tag{5.3}$$

The minimum number of atoms which must be cycled to obtain a change in $\overline{\alpha l}$ of a factor of 2, N_c, is one fourth of the atoms in state 1, or utilizing the requirement that $\overline{\alpha l} \geq 1$,

$$N_c \gtrsim \frac{\pi^3}{F}\frac{a_w}{\lambda^2}\frac{(\Delta\nu_0+\Delta\nu_p)}{\gamma_s}\ . \tag{5.4}$$

Thus, N_c scales linearly with the switching element cross section a_w and inversely with the resonator finesse. The dependence on the linewidth $\Delta\nu_p$ is examined by introducing the minimum bandwidth $\Delta\nu_w$ allowed by the uncertainty principle for an atomic level or resonator mode which has a lifetime γ_w^{-1}. Thus,

$$\Delta\nu_w=\gamma_w/2\pi \ . \tag{5.5}$$

There are two principal regimes of interest, $\Delta\nu_0>\Delta\nu_w$ and $\Delta\nu_w>\Delta\nu_0$ (this latter case corresponds to operating the switch in a condition where lifetime broadening is large compared to other broadening mechanisms). For the former case $\Delta\nu_p$ can be made of the order of $\Delta\nu_w$ and neglected in comparison to $\Delta\nu_0$. In that case,

$$N_c \ge \frac{\pi a_w}{4F\sigma} \ , \tag{5.6}$$

where the atomic cross section

$$\sigma=\frac{\lambda^2}{4\pi^2}\frac{\gamma_s}{\Delta\nu_0} \ . \tag{5.7}$$

The minimum value of N_c is obtained, for given a_w and σ, by taking the maximum value of F with $\xi=1$. This gives

$$N_c \ge \frac{1}{4}\frac{v_w\gamma_w}{\sigma v} \ . \tag{5.8}$$

Assuming that F can be optimized and the approximations used to obtain (5.8) are satisfied, the switch volume and the atomic cross section are the sole determinants of the minimum number of atoms and, hence, the minimum thermal energy which must be dissipated in the switch. Of course, if N_c becomes sufficiently small, reliability considerations will place limits on the minimum value of N_c.

For nonresonant interactions the minimum switching energy is calculated in a way similar to that above. The refractive index at frequency ν for a gain coefficient $\alpha(\nu)$ is (for n_r-1 and $\alpha\lambda/2\pi$ small compared to n_r)

$$n_r(\nu)-1=\frac{\alpha(\nu)\lambda}{2\pi}\frac{(\nu-\nu_0)}{\Delta\nu_0} \ . \tag{5.9}$$

Assuming that the optical field is sufficiently far from resonance that $\nu-\nu_0$ can be treated as a constant, the number of atoms N_c which must undergo a change of state to satisfy the switching condition is one fourth of the number required to satisfy

$$n_r-1=\frac{\lambda}{2Fl_w} \ . \tag{5.10}$$

Thus, for $\Delta\nu_0>\Delta\nu_w$

$$N_c=\frac{\pi^3}{F}\frac{\Delta\nu_0}{\gamma_s}\frac{a_w}{\lambda^2}\chi(\nu) \ , \tag{5.11}$$

where

$$\chi(\nu)=\frac{[\Delta\nu_0^2+4(\nu-\nu_0)^2]}{\Delta\nu_0(\nu-\nu_0)} \ . \tag{5.12}$$

For the case $\Delta\nu_0<\Delta\nu_w$, a similar result is obtained. Thus, nonresonant interactions require switching energies which are larger than those for resonant interactions by approximately the number of bandwidths of detuning from the atomic resonance.

The maximum switching rate can be expressed in terms of N_c as

$$\gamma_w<(N_c)^{1/2}\left[\frac{\nu\gamma_s}{\pi}\right]^{1/2}\left[\frac{\lambda^3}{v_w}\right]^{1/2} \ . \tag{5.13}$$

The corresponding finesse for $\xi=1$ is

$$F=\frac{\pi\lambda}{l_w}\left[\frac{\pi\nu}{\gamma_s}\right]^{1/2}\left[\frac{v_w}{\lambda^3}\right]^{1/2}N_c^{-1/2} \ . \tag{5.14}$$

This case represents the maximum rate for an idealized switch and hence serves to identify a limiting condition rather than a typical operating regime.

The maximum thermal energy generated in the switching element per cycled atom is $h\nu$. Conservative estimates of performance should use this value. In the interest of exploring absolute limits, however, we also consider the case where some fraction of the switching energy is removed from the switching element as light. If spontaneous emission is excluded, then the only way of extracting a signficant portion of the excited atom energy as light, is through stimulated emission. Such a procedure requires population inversion. In general, to obtain a relaxation rate from level 2 to level 3, sufficient to maintain $N_1>N_2$, the transition 2 to 3 will have to be nonradiative. In that case an energy $h\Delta\nu_{23}$ must be dissipated in the switch and the problem of minimizing the thermal energy per cycled atom becomes that of minimizing $\Delta\nu_{23}$ consistent with the need to maintain a population inversion.

For the case $kT \gg \hbar\gamma_w$, the principal mechanism leading to population of level 2 is thermal population of level 2 from level 3. The number of atoms in level 2 for N_3 ground-state atoms and a Boltzmann distribution is

$$N_2=N_3\exp(-h\Delta\nu_{23}/kT) \ . \tag{5.15}$$

To obtain population inversion under saturation of the transition $3\rightarrow1$ by a pump requires a thermal energy u_t dissipated in the switch

$$u_t \ge N_c kT \ln 2 \ . \tag{5.16}$$

Another limiting case occurs for $kT \ll \hbar\gamma_w$.

There the broadening of the levels due to the finite lifetime will cause the ground-state ions to absorb light of frequency ν_{12} even if kT is negligibly small compared to $h\Delta\nu_{23}$. Again under saturation of $3\rightarrow1$ as above, a Lorentzian line shape and a relation $\Delta\nu_w=\gamma_w/2\pi$ gives

$$\Delta\nu_{23}>\gamma_w/4\pi\ . \tag{5.17}$$

In this case the minimum energy which must be dissipated in the switch, if N_c excited atoms undergo transitions, is

$$u_t>N_c\hbar\gamma_w/2\ . \tag{5.18}$$

In principle, the use of reversible processes could yield switches which generated no thermal energy per switching operation.[15] While those possibilities could be important and perhaps more easily realized in optical switches than other switches (as by use of virtual transitions, e.g.), we use 5.16 and 5.18 as lower limits on u_t for this paper.

For the idealized case under discussion, the thermal energy which must be generated in a switching element is then

$$u_t=\zeta N_c h\nu\ . \tag{5.19}$$

Here, ζ plays the role of the probability that the quantum of energy used to cycle an atom must be left in the switch as heat. The lower limits on ζ are $kT\ln 2/h\nu$ for $kT>\hbar\gamma_w$ and $\gamma_w/4\pi\nu$ for $kT<\hbar\gamma_w$. Utilizing the expression for N_c developed above, we have

$$u_t\geq\frac{\pi\zeta a_w}{4F\sigma}h\nu\ . \tag{5.20}$$

If F has its maximum value, then

$$u_t\geq\frac{\zeta}{4}\frac{v_w}{\sigma\lambda}h\gamma_w\ . \tag{5.21}$$

The minimum switching energy required for a representative switching rate of 10^{12} sec^{-1} is plotted versus atomic cross section in Fig. 3. The following three cases are considered: (a) $\zeta=1$, (b) $\zeta=(kT\ln 2)/(h\nu)$ for $T=300$ K, and (c) $\zeta=\gamma_w/2\pi\nu$. The curves indicate the minimum energy required by the above expressions. The solid lines indicate the range of switching energies limited by an upper bound imposed by the capacity of typical optical materials to dissipate heat and by a lower bound imposed by the need for reliable switching. (See Sec. VI below.) The maximum cross section for existing solid-state laser transitions is indicated by σ_m.[16]

A rather rapid switching rate $\gamma_w=10^{12}$ sec^{-1} has been chosen here to illustrate the nature of the optical switching problem. The principal point to be made is that, while the acceptable operating range for a switch with $\zeta=1$ and $\gamma_w>10^{12}$ (for unit duty cycle) is small, there are various ways of easing the constraints. For example, the range of operating conditions can be increased by modest reductions in γ_w. Also, the duty cycle can be reduced, or the amount of heat generated per cycled atom reduced below $h\nu$ so as to yield acceptable levels of heat dissipation [curves (b) and (c), e.g.]. A general rule is that the thermal energy is minimized by minimizing switch dimensions and maximizing σ or γ_s, whichever is relevant.

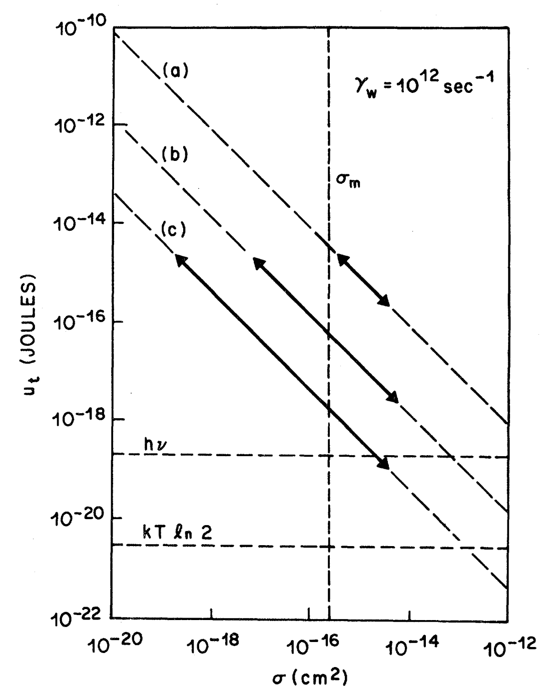

FIG. 3. Illustrative example of minimum energy dissipated in the switch vs cross section [for $\gamma_w=10^{12}$ sec^{-1}, and (a) one quantum dissipated per cycled atom (b) $kT\ln 2$ dissipated per cycled atom for $T=300$ K (c) $h\gamma_w/2\pi$ dissipated per cycled atom]. Thermal energy per switching operation for one quantum and for $kT\ln 2$ ($T=300$ K) dissipated in the switch is indicated by dashed horizontal lines. Vertical line labeled σ_m indicates the maximum cross section for known solid-state laser transitions providing gain.

Consider the problem of maximizing the ratio of stimulated emission to spontaneous emission. A major difficulty occurs in that the same changes which minimize switching energy also increase the rate of spontaneous emission. Some of this increase is avoidable, and some is not. One source of enhanced spontaneous emission rate is cooperative spontaneous emission or superfluorescence. This enhancement can be large, but is often avoidable. The rate of superfluorescence[17] for the case of N_1 excited ions is

$$\gamma_{sf}=\gamma_s(\mu N_1+1) \ . \tag{5.22}$$

Here μ is a shape dependent factor. For example, for the special case $l_w \gg \lambda/2\pi$ and $a_w \gg \lambda l_w$,[17]

$$\mu=\frac{3}{8}\frac{\lambda}{l_w} \ . \tag{5.23}$$

The principal point is that μ tends to approach unity for atomic systems with dimensions of optical wavelengths. Thus, the spontaneous emission rate can be greatly enhanced ($\gamma_{sf} \gg \gamma_s$) if N_1 is relatively large and the switch dimensions small. These conditions are, however, highly likely in an optimized switch, and hence, consideration must be given to the problem of reducing γ_{sf}.

If dephasing collisions or inhomogeneous broadening are present which lead to a full width at half maximum of the atomic linewidth of $\Delta\nu_0$, then a factor enters in calculating the build up of superfluorescence[17] of

$$H(t)=e^{-2\Delta\nu_0 t} \ , \tag{5.24}$$

where t is time measured from the point when the atoms are introduced into the excited state. Equation (5.24) ensures that for

$$\Delta\nu_0 \gg \gamma_{sf} \tag{5.25}$$

superfluorescence will be unimportant. The preferred strategy thus appears to be to choose transitions which are broadened by dephasing, or inhomogeneous broadening, mechanisms up to the point where $\Delta\nu_0$ approaches the value which would lead to degradation of switch performance, i.e.,

$$\Delta\nu_0 \lesssim \frac{\gamma_w}{2\pi} \ . \tag{5.26}$$

If superfluorescence is to be suppressed without otherwise degrading switch performance, it is thus necessary that

$$\gamma_w > \gamma_{sf} \ . \tag{5.27}$$

The preferred conditions can be obtained through the use of (5.13) and (5.22). For $\mu N_1 \gg 1$ and $N_c = N_1/4$ the ratio γ_w/γ_{sf} is

$$\frac{\gamma_w}{\gamma_{sf}}=\frac{F}{\pi\mu}\frac{\lambda^2}{a_w} \tag{5.28}$$

or, through the use of μ given by (5.23),

$$\frac{\gamma_w}{\gamma_{sf}}=\frac{8Fl_w\lambda}{3\pi a_w} \ . \tag{5.29}$$

Thus, even in the worst case ($l_w\lambda/a_w=1$) the condition $\gamma_w \gg \gamma_{sf}$ can be assured by making $F \gg 1$, which is usually desirable for other reasons. In that case, $\Delta\nu_0$ can be made comparable to γ_w and superfluorescence can be suppressed without sacrificing switching rate. It does appear, however, that a high-finesse resonator, and a value of $\Delta\nu_0$ approaching γ_w, are both necessary for a minimization of optical noise generation for $N_1 \gg 1$.

The residual spontaneous emission rate which is not further reducible for an excited atom in a resonator of finesse F is[18]

$$\gamma_s'=\frac{\gamma_s F\lambda^2}{2\pi^2 a_w} \ . \tag{5.30}$$

That is, while a microresonator enhances the rate of stimulated emission, the rate of spontaneous emission is also enhanced. For a single switching element, the ratio of the two rates is still given by the number of quanta in the mode of the radiation field acting on the excited atom, although both rates are enhanced. For a two-element switch, it appears possible to improve on this ratio (see Sec. VIII, below).

A degree of uncertainty will always be present in an optical switching operation because of uncertainties in predicting the outcome of the atom-photon interaction. It can be shown, however, that the probability of a given outcome of a switching operation is described approximately by a Poisson distribution. Thus, in general, if the number of quanta and number of cycled atoms is large compared to one (e.g., ~ 1000), the outcome can be predicted with a very high degree of reliability.[19] We thus use 10^3 as a nominal lower limit on N_c throughout.

VI. DISSIPATION OF EXCESS SWITCHING ENERGY

We use a highly approximate model to make order-of-magnitude estimates of heat dissipation by thermal conduction (Fig. 4). Heat generation is assumed to occur in a core region of uniform temperature T, and conduction of heat to occur through a surrounding shell of thermal conductivity κ to an external surface at uniform temperature T'. A description of heat dissipation by conduction can be obtained from the equations for steady-state heat conduction in simple bodies. For the geometries

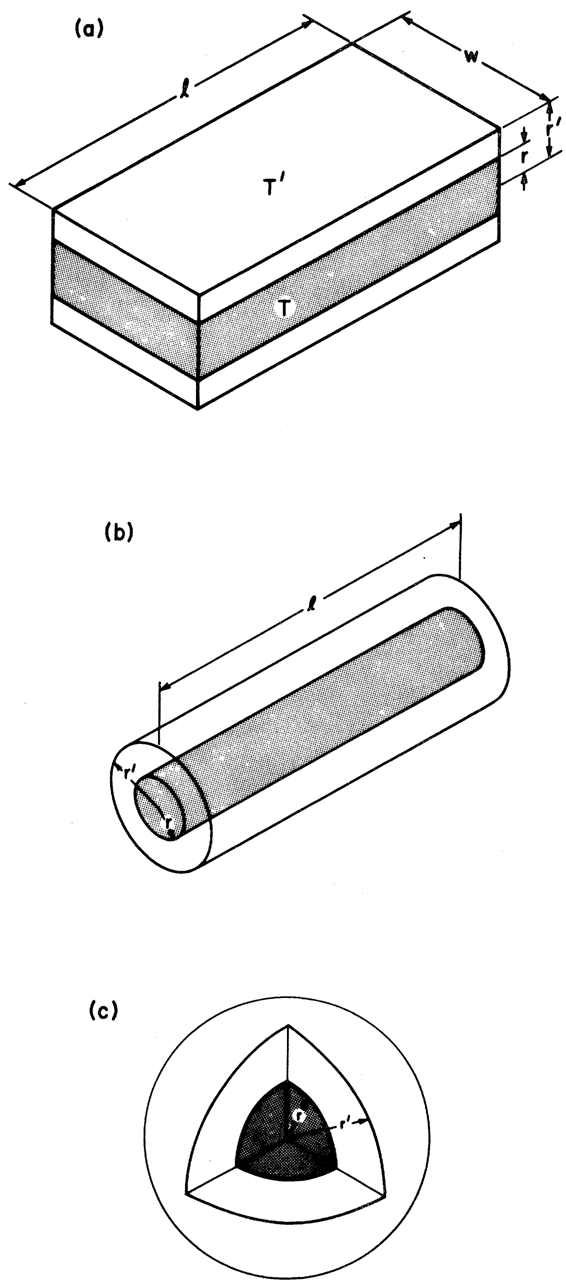

FIG. 4. Model structures for the case of (a) slab, (b) cylindrical, and (c) spherical geometries. Heat-generating region occupies the shaded portion of the element and is at a temperature T. External surface is at a temperature $T' < T$.

shown in Fig. 4, the power which can be removed by conduction is (for slab, cylinder, and sphere, respectively)

$$p_t' = \frac{2\kappa l w (T'-T)}{(r'-r)} , \tag{6.1}$$

$$p_t' = \frac{2\pi\kappa l (T'-T)}{\ln(r'/r)} , \tag{6.2}$$

$$p_t' = \frac{4\pi\kappa r (T'-T)}{(1-r/r')} . \tag{6.3}$$

(We use p_t' to denote the power which can be removed from the switch by conduction and p_t below to denote the power generated in the switch by the atomic system. The other parameters are identified in Fig. 4, except for κ, which is the thermal conductivity of the material through which the heat is flowing.) These equations are given by Jakob who discusses them in greater detail.[20] For our pupose they are useful as long as κ can be approximated as temperature independent, the difference between r' and r approximates the distance through which heat must be conducted, the phonon free path is short compared to $r'-r$, and interfaces between different materials do not introduce pronounced thermal barriers.[21] We use these equations below to calculate the rate at which a given switch can be operated for a given temperature rise.

VII. LIMITS ON SWITCHING ELEMENT CAPABILITY

Limits on switch capability for the idealized case under discussion can be identified by combining the expressions for switching rate and the expressions for the dissipation of switching energy. This section develops the resulting expressions in terms of a characteristic parameter l_0 which has the dimensions of length

$$l_0 = \frac{h\nu^2}{\kappa \Delta T} . \tag{7.1}$$

Here ΔT is the temperature difference $T'-T$ for the switch. For thermal conductivities typical of optical materials, ν an optical frequency, and conservative values of ΔT, l_0 is of the order of optical wavelengths. For example, for $\kappa = 0.1$ W cm^{-1} K^{-1}, $\Delta T = 10$ K and $\nu = 3\times 10^4$ sec^{-1}, $l_0 = 0.6$ μm.

The number of atoms which can be cycled per switching event is obtained by setting the minimum power which must be dissipated in the switch (for N_c atoms cycled per switching event) equal to the maximum power which can be conducted from the switch. This yields

$$N_c \le \frac{d\nu}{\zeta l_0 \gamma_w} . \tag{7.2}$$

Here, d is a parameter with the dimensions of a length which depends on the geometry of the switch. It can be obtained for a given geometry through the use of the expressions in Sec. VI. For example,

$$N_c \leq \frac{2\pi}{\zeta \ln 2} \frac{l_w \nu}{l_0 \gamma_w} \tag{7.3}$$

for a cylindrical switch with $r'=2r$ (see Fig. 4 for the meaning of r' and r).

The maximum value of γ_w permitted for a given value of l_0 is

$$\frac{\gamma_w}{\nu} \leq \frac{4F}{\pi\zeta} \frac{d\sigma}{l_0 a_w} . \tag{7.4}$$

If the finesse F has its maximum value for $\xi=1$, γ_w is (for $\Delta\nu_0 > \Delta\nu_w$) given by

$$\frac{\gamma_w}{\nu} = \left[\frac{4}{\zeta} \frac{d\lambda\sigma}{l_0 v_w}\right]^{1/2} . \tag{7.5}$$

Consider, for example, the case where $\Delta\nu_0 > \Delta\nu_w$, and the switch has cylindrical geometry with $r_w'=2r_w$, and $r_w=\lambda$, then

$$\frac{\gamma_w}{\nu} = \left[\frac{8}{\zeta \ln 2} \frac{\sigma}{l_0 \lambda}\right]^{1/2} . \tag{7.6}$$

The values of γ_w permitted by the above expression are plotted versus σ in Fig. 5 assuming $\lambda=0.7$ μm and $l_0=0.6$ μm for (a) $\zeta=1$, (b) $\zeta=(\ln 2kT)/h\nu$, and (c) $\zeta=\gamma_w/2\pi\nu$.

As an additional example consider the case where $\Delta\nu_w > \Delta\nu_0$, $r'=2r$, and $r=\lambda$ for a cylindrical switch as above. Then the switching rate is

$$\frac{\gamma_w}{\nu} = \left[\frac{2}{\pi\zeta \ln 2} \frac{\lambda}{l_0} \frac{\gamma_s}{\nu}\right]^{1/3} \tag{7.7}$$

or, if ζ has its minimum value,

$$\frac{\gamma_w}{\nu} = \left|\frac{16}{\ln 2} \frac{\lambda}{l_0} \frac{\gamma_s}{\nu}\right|^{1/4} . \tag{7.8}$$

Plots of γ_w vs γ_s given by (7.7) and (7.8) are shown in Fig. 6 for a typical value of l_0 and the three values of ζ given above. A feature common to both Figs. 5 and 6, but more pronounced in Fig. 6, is the relatively weak dependence of the switching rate on the atomic parameters. In particular, the dependence is weaker the more highly optimized the switch.

As mentioned above, a limit on the minimum number of cycled atoms occurs due to the need to obtain reliable switching. That is, if the value of N_c becomes so small that reliability considerations prevent further reductions, then N_c must be taken as a fixed parameter. Let the minimum value of N_c permitted by statistical considerations be N_n. Then the switching rate is limited by

$$\gamma_w \leq \frac{d\nu}{\zeta l_0 N_n} . \tag{7.9}$$

For the case of a cylindrical switch

$$\frac{\gamma_w}{\nu} < \frac{2\pi}{\ln(r'/r)} \frac{l_w}{l_0} \frac{1}{\zeta N_n} . \tag{7.10}$$

Inserting the maximum value of l_w gives

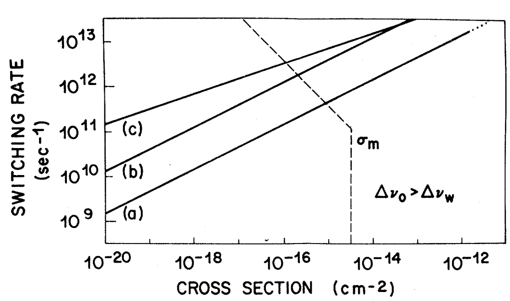

FIG. 5. Illustrative example of maximum switching rate vs cross section for a cylindrical switch (for $\Delta\nu_0 > \Delta\nu_w$, $r_w'=2r_w$, $r_w=\lambda$, $l_0=0.6$ μm, $\lambda=0.7$ μm, and $\nu=3\times10^{14}$ sec^{-1}). All points on the solid lines in this figure and Fig. 6 are allowed both by thermal limits and the lower limit on the number of cycled atoms imposed by the need for reliable operation ($N_c \gtrsim 10^3$). Amount of heat dissipated per cycled atom is the same in curves (a), (b), and (c) as in Fig. 3. Reduction in the effective values of σ_m caused by lifetime broadening (i.e., violation of the condition $\Delta\nu_0 > \Delta\nu_w$) is indicated by the slanted dashed line.

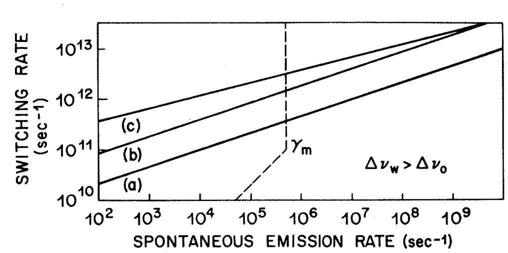

FIG. 6. Illustrative example of maximum switching rate vs spontaneous emission rate for a cylindrical switch (for $\Delta\nu_w > \Delta\nu_0$, $r_w'=2r_w$, $r_w=\lambda$, $\lambda=0.7$ μm, $l_0=0.6$ μm, and $\nu=3\times10^{14}$ sec^{-1}). Curves (a), (b), and (c) have the same meaning as in Fig. 3. [Maximum spontaneous emission rate for solid-state independent-atom transitions which yield gain is indicated by the dashed vertical line. Apparent reduction in γ_m caused by nonradiative broadening (i.e., violation of the condition $\Delta\nu_w > \Delta\nu_0$) is indicated by the slanted dashed line.]

$$\frac{\gamma_w}{\nu} < \left[\frac{2\pi^2}{\ln(r'/r)}\frac{\lambda}{l_0}\frac{1}{\zeta F N_n}\right]^{1/2} . \tag{7.11}$$

This sets the upper limit on γ_w imposed by N_n. The region of the switching rate curves where (7.11) is violated in Figs. 5 and 6, for $N_n = 1000$, is indicated by a dotted line [curve (c) in Fig. 5].

Although it is difficult to predict the nature of optical systems, we can make an order-of-magnitude estimate of the limit set on element density in a system. For example, we assume a system having spherical geometry with the heat-generating region in a core as in Fig. 4 and $r' \gg r$. Then, where p_t is the thermal power generated by each switching element, the upper limit on element density is

$$N_v = \frac{4\pi\kappa_y \Delta T_y}{r_y^2 p_t} . \tag{7.12}$$

Here, k_y is the thermal conductivity of the material used to conduct heat out of the system, ΔT_y is the acceptable temperature differential $T' - T$, and r_y is the radius of the heat-generating region. A plot of N_v vs p_t utilizing the above expression is given in Fig. 7 for three values of r_y and representative values of κ_y and ΔT_y.

The thermal limits on element density, for these particular conditions, are thus typically more severe than those imposed by the limit $N_v < \lambda^{-3}$. In general, thermal limits will predominate unless the switching element dimensions are large compared to optical wavelengths, or the power dissipated per element becomes small ($\lesssim 10^{-6}$ W), and the system dimensions become small ($\lesssim 1$ mm). The conclusions to be drawn from the curves in Figs. 5–7, and the analysis in general, are discussed in Sec. IX.

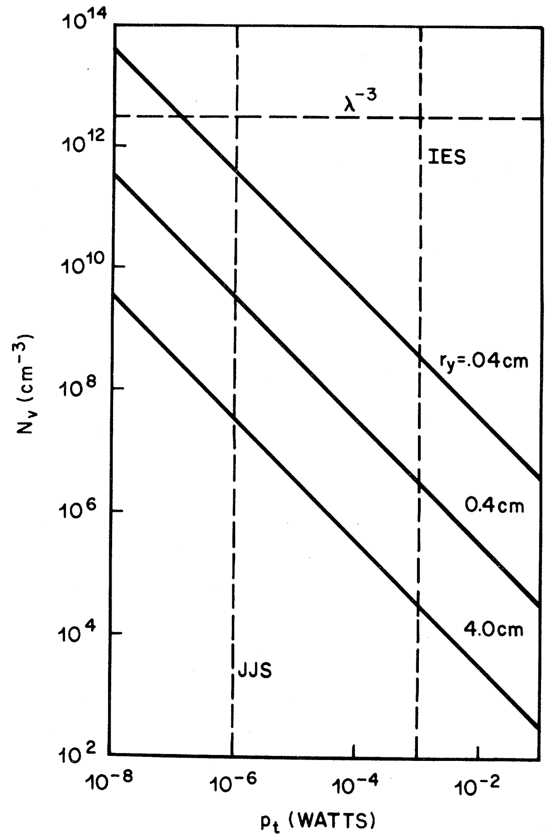

FIG. 7. Illustrative example of maximum element density vs average power dissipated per switching element for a small spherically shaped system (for $K_y = 4$ W cm^{-1} K^{-1}, $\Delta T = 10$ K, and $r_y = 0.04$, 0.4, and 4.0 cm). Horizontal line indicates the maximum element density set by the restriction that $\nu_w > \lambda^3$ for $\lambda = 0.7$ μm. Vertical lines indicate representative power dissipation levels for the case of integrated electronics switches (IES) (e.g., for $u_t \cong 10^{-12}$ J and $\gamma_w \cong 10^9$ sec^{-1}), and for Josephson junction switches (JJS) (e.g., for $u_t \cong 10^{-18}$ J and $\gamma_w \cong 10^{12}$ sec^{-1}).

VIII. SWITCH DESIGN

A model switch is described here which permits, in principle, realization of the capabilities listed in Sec. IV, as well as the switching rates calculated in Sec. VII. While actual switches can be expected to depart markedly from this model switch, it is useful as an existence proof. The switch consists of an astable laser oscillator and two control switches (Figs. 8 and 9). The oscillator consists of a primary resonator of finesse F_p, length l_p, and cross section a_p, and a gain region containing N_p excited atoms of cross section σ_p. The control switches each contain a set of N_q atoms of cross section σ_q ($q = A,B$, see Fig. 8) which are acted upon by the switching pulse. [The approximation is used throughout this section that all the atoms which interact with the oscillator mode of frequency ν_0 in a given switching element are either entirely in the emitting state (state 1), or entirely in the absorbing state (state 3).]

The net single-pass gain for $\nu = \nu_0$ for the oscillator exclusive of the control switches is just the gain of the atomic system less the single-pass-resonator loss, or

$$\alpha_0 l_p = \frac{N_p \sigma_p}{a_p} - \frac{\pi}{F_p} . \tag{8.1}$$

Thus, $N_p \sigma_p F_p / \pi a_p$ must be significantly larger than one if the oscillator is to approach saturation at a rate comparable to the switching rate derived above.

The switching gain G of the switch, i.e., the ratio of the number of quanta in the switched pulse to the number of quanta in the matching pulse, is given approximately by

$$G \le N_p/N_{cq} \; . \tag{8.2}$$

Here, N_{cq} is the number of cycled atoms in the control switch. A special problem arises in that large G requires $N_p \gg N_{cq}$, in which case the control sections (utilizing resonant interactions) can be used to allow or prevent the initiation of laser oscillation, but are not adequate to terminate laser action. The solution here is to design the laser as a self-terminating *astable* oscillator, as, e.g., by giving the lower laser level a sufficiently slow relaxation rate so as to cause termination of laser oscillator action in a time of order γ_w^{-1}.

Since the control regions must provide a gain or loss comparable to $N_p\sigma_p/a_p$ to exert control over the primary laser oscillator, but must not yield a significantly larger loss or gain,

$$\sigma_c N_q \cong \sigma_p N_p \tag{8.3}$$

is required. Thus, the switching gain is also given approximately by

$$G \lesssim \frac{\sigma_c}{\sigma_p} \; . \tag{8.4}$$

An absorption control switch [Fig. 9(a)] adds a

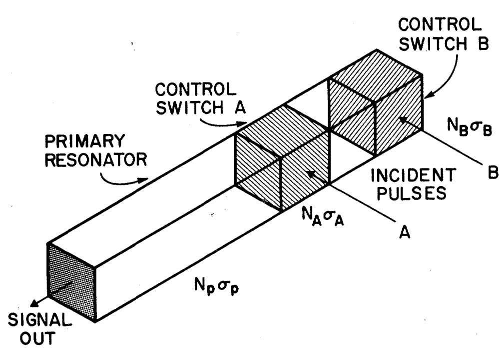

FIG. 8. Model optical switch. Switch consists of a primary switching element having a resonator which includes an atomic system having N_p excited atoms of cross section σ_p and two control switches A and B. Control switches contain N_A atoms of cross section σ_A, and N_B atoms of cross section σ_B, respectively, and have spatial cross sections normal to the axis of the primary resonator which are the same as that of the primary resonator.

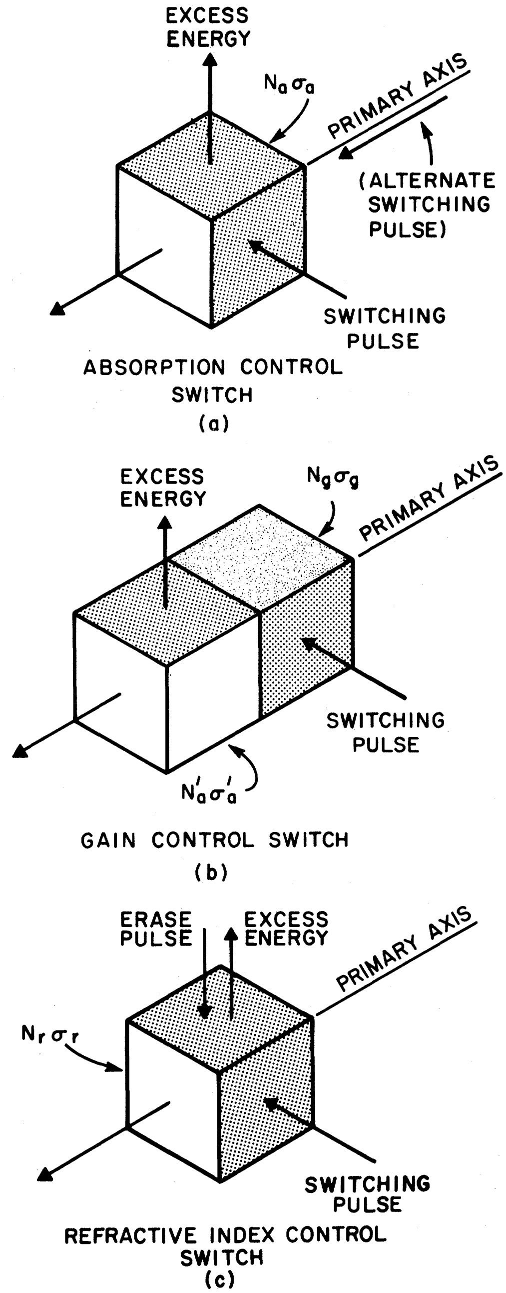

FIG. 9. (a) Absorption control switch. This switch consists of an atomic system of the type shown in Fig. 1(b) with N_a atoms of cross section σ_a in level 3 in the absence of saturation. (b) Gain control switch. This switch consists of an absorption element and a gain element. Absorption element has an atomic system of the type shown in Fig. 1(b) with N'_a atoms of cross section σ'_a in level 3 in the absence of saturation. Gain element has an atomic system of the type shown in Fig. 1(a) with N_g atoms of cross section σ_a in level 1, and no atoms in level 2, in the absence of saturation. (c) Refractive-index control switch. This switch consists of an atomic system of the type shown in Fig. 1(c) or 1(d).

region of saturable absorption to the primary resonator. The net single-pass gain for the primary oscillator is then

$$\alpha_0 l_p = \frac{N_p \sigma_p}{a_p} - \frac{N_a \sigma_a}{a_p} - \frac{\pi}{F_p} . \tag{8.5}$$

Here N_a is the number of absorbing atoms in the absorption control element and σ_a is the cross section for those absorbing atoms. By choosing $N_a \sigma_a$ properly, $\alpha_0 l_p$ can be changed from negative to positive on saturating the atomic system of the absorption control switch. A single such switch introduced as switch A provides the A ignore B operation. Two such switches provide either the AND operation, or the OR operation, depending on the value of the primary gain.

A gain control switch [Fig. 9(b)] adds matching regions of saturable gain and absorption to the primary resonator. The net single-pass gain for an oscillator including such an element is

$$\alpha_0 l_p = \frac{N_p \sigma_p}{a_p} + \frac{N_g \sigma_g}{a_p} - \frac{N_a' \sigma_a'}{a_p} - \frac{\pi}{F} . \tag{8.6}$$

Here the number of atoms providing gain in the gain element of the gain control switch is N_g, and the cross section of those atoms is σ_g. The number of absorbing atoms in the absorbing element of the gain control switch is N_a', and the cross section of those atoms is σ_a'. The parameters are to be chosen so that $\alpha_0 l_p$ is positive when N_g has its maximum value, and negative when it has its minimum value. Thus, the gain control element enables the switching pulse to have an inhibitory effect on the oscillator.

Another form of control switch [Fig. 9(c)] can be realized in the form of a refractive-index control switch by using atomic systems of the type indicated in Figs. 1(c) and 1(d). In this switch, the effect of the switching pulse is to alter the refractive index of the region occupied by the control switch. This switch is necessarily less efficient than a gain or absorption control switch by a factor of the order of the number of bandwidths of detuning. However, an advantage is gained in that the laser oscillator fields have a weak influence on the control region.

The contrast ratio (i.e., the ratio of stimulated emission to spontaneous emission) of the model switch can be enhanced over that of a single switching element, by including a saturable absorption control section. That is, if the noise level due to spontaneous emission is too weak to saturate the absorption control element, that noise level will be reduced by the absorption of the control element. In that case, assuming the signal pulse contains enough quanta to saturate the absorption control element, the contrast ratio would be enhanced by a factor

$$\eta_e \cong \exp \frac{N_a \sigma_a}{a_a} , \tag{8.7}$$

where N_a is the number of atoms in the absorption control element, σ_a is their cross section, and a_a is the cross section of the absorption control element.

By proper combination of the various types of switching elements this switch will exhibit all of the switching operations such as AND, OR, NOT, etc. It will also exhibit bistable operation in the sense of emitting or not emitting a continuous pulse train depending on its previous history.

IX. CONCLUSIONS

It is concluded that optical switching systems with extremely high capacities are allowed by fundamental laws. However, it is also concluded that the problems of realizing the large interaction cross sections and high-finesse microresonators recommended by the analysis are so difficult that solutions will require an improved understanding of optical interactions in solid-state materials, and possibly novel physical discoveries. The nature of these problems is discussed in Sec. I and possible attacks on them are examined below.

It does appear that it will be necessary to cycle a number of atoms large compared to one in order to achieve reliable optical switching and that a number of quanta of energy $h\nu$ also large compared to one will be required to cycle those atoms. It does not appear necessary, however, that all of the optical switching energy be dissipated in the optical switch or that optical switches are necessarily inferior to other switches[22] as regards the energy which must be dissipated in the switching elements.

The fundamental limit on optical switch volume of λ^3 is larger than the lower limit on volume for alternative switches based on electronic phenomena.[22] This does not, however, appear to be a serious limit from a practical point of view in systems employing high switching rates. That is, for high switching rates, thermal limits are likely to intervene before size limits of the order of λ^3 become important. From a fundamental point of view, this is not an entirely rigid limit, since λ is the wavelength of the optical frequency excitation in the material. That is, λ is reduced from λ_0, the vacuum wavelength, by the ratio v/c, so that λ^3 can, in principle, be considerably smaller than λ_0^3.

Optical switches do appear to possess a fundamental advantage as switching rates approach optical frequencies. That is, the only switches which are capable of closely approaching optical frequency switching rates in the foreseeable future are optical switches. Also, since the velocity of light is the known upper limit on propagation velocity, there are no known means of transferring switched information from point to point more rapidly.

A few rather general rules concerning design strategy emerge from the discussion. One rule is that the switch dimensions should be reduced as closely as possible to the order of optical wavelengths. There are two physical mechanisms which both favor such a reduction. The acceptable thermal power density increases quadratically with the reciprocal of the minimum switch dimension, and the minimum number of cycled atoms decreases as the volume of the switching element decreases. The combination of both these sensitive dependences on switching element dimensions strongly recommends minimization of the switch dimensions. Also, the need to be competitive with alternative switches requires an approach of those dimensions to optical wavelengths.

A second closely related rule is that the performance of an optical switch can usually be improved by a resonator. The resonator confines the optical fields and increases the field energy density in the switch for a given switching energy. Since the required switching energy decreases with increasing resonator finesse it is desirable to maximize the finesse consistent with avoiding a reduction in switching rate. (The energy density can also be increased through the use of short pulses and traveling wave interactions. This is useful but leads to reduced switching element densities since the switch length must be increased by a factor of order F over a comparable switch utilizing a resonator of finesse F.)

A third rule is that the fraction of the quantum energy dissipated in the switch per cycled atom, ζ, should approach, as closely as possible, the minimum calculated above. That is, the minimum value of ζ calculated in Sec. V is usually small compared to one, and realization of the full capability of an optical switch depends on minimizing ζ.

A fourth rule is that the cross section, spontaneous emission rate, or other measure of the strength of the interaction between the atomic system and optical field should be maximized, preferably to the point where statistical considerations intervene. The argument is that the required switching energy decreases with increasing interaction strength until the point is reached where statistical considerations prevent a further reduction in the number of cycled atoms. While the increase in switch performance with increasing σ or γ_s can be relatively slow, especially in a well optimized switch, it can still be decisive as regards realization of an optical switch competitive with alternative switches.

A fifth rule is that processes involving virtual interactions in which all the switching energy is removed from the switch as light should be considered. The removal of the entire switching energy from the switch as light is a feature unique to optical switches and deserves exploration.

Some incidental design considerations are (1) it is highly likely that solid-state materials will be required. Two of the many reasons for requiring solid-state materials are the need for extremely large gain per unit distance and the need for a matrix which maintains a well-defined spatial relationship between switches. (2) Maximization of signal to noise will probably require realizing gain in a nonlinear device which is more complex than a single element.

The problem of selecting a research strategy is a highly individual matter, and the interested reader will persumably devise his own. As a possible aid, however, the above findings are summarized in the form of three rules and several observations are offered. The rules are that the degree to which an optical switch approaches its potential is measured in large part by the degree to which (1) the dimensions of the switch approach optical wavelengths, (2) the interaction matrix element for the moment of the atomic system and the optical field (at the excitation level of a single quantum) approaches optical energies, and (3) the fraction of the switching energy which is removed from the switch as light approaches unity. While it will usually be neither possible, nor desirable, to achieve these limiting cases, the need to approach those cases in some degree is likely to shape most strategies.

A number of problems which make it difficult to realize competitive optical switches are eased as the optical switching rate approaches optical frequencies. For example, shortening the pulse localizes the optical energy in a smaller volume even in the absence of a resonator, and if a resonator is used, the finesse required for a given degree of localization decreases linearly with pulse duration. Also, degradation of the switch performance due to competing nonradiative relaxation, spontaneous emission, or a given degree of line broadening is reduced. Finally, there is the obvious point that alternative switches cannot compete at all, once the switching rates exceed certain values (e.g., $\sim 10^9-10^{11}$ $\sec^{-1}$ for integrated electronics and $10^{11}-10^{12}$ $\sec^{-1}$ for Josephson junction switches).

Another observation is that the problem of interactions between the atomic system and the optical fields in which the atoms of the atomic system behave cooperatively is particularly important. The argument is that for fundamental, and perhaps unavoidable reasons, the interaction matrix element in the independent-atom approximation (in solid-state materials, where practical optical switches are most likely to be realized) falls many orders of magnitude below its theoretical maximum. This problem has such a fundamental character that it appears very difficult to improve upon. A potential solution is, however, offered by cooperative interactions. That is, given N cooperating ions within a volume small compared to λ^3, the rate of transfer of energy between the atomic system and optical field can be increased by a factor of order N over that for an isolated atom for the same investment of energy.[23] Another way of making a comparision which is relevant for systems not small compared to λ^3 is in terms of the polariton frequency ν_p.[11] If the excited atomic system can be approximated as an exciton having the optical wave vector, then the rate of transfer of energy between the atomic system and the optical fields is

$$\nu_p=\omega_p(f/4\epsilon)^{1/2} \tag{9.1}$$

(where ω_p is the plasma frequency[24] and ϵ is the dielectric constant of the host crystal). The oscillator strength f for the transition moment μ_{ij} is

$$f=\frac{8\pi^2 m\nu}{3he^2}\,|\mu_{ij}|^2\,, \tag{9.2}$$

where m is the electron mass and e is the electron charge. The frequency ν_p is always much larger than the comparable parameter for the independent-atom case. That is, since $\omega_p \cong 3\times 10^{15}$ $\sec^{-1}$, ν_p can be of the order of $10^{11}-10^{12}$ $\sec^{-1}$, even for highly forbidden transitions (where $f\approx 10^{-6}$).

The exact manner in which cooperative interactions might be used for efficient optical switching remains a reseach problem; however, several observations can be advanced. For example, cooperative interactions which require a large number of excited atoms, with excitation energies of order $h\nu$, such as super-radiant states, to establish the cooperative behavior do not offer much advantage. That is, the need for a large number of quanta defeats the original purpose in seeking cooperative behavior. Also, the polariton interaction alone does not offer obvious advantages since, in the absence of nonradiative coupling of the atoms, it introduces no features not already present in the independent atom model. The physics most likely to yield competitive optical switches thus appears to lie in novel combinations of radiative and nonradiative interactions which possess a cooperative character at low excitation levels.

One class of examples where nonradiative interactions can be used to obtain efficient switching is the change in the enhanced absorption near the band edge of a semiconductor caused by introduction of photoexcited carriers.[25] There the photoexcited carriers alter carrier interactions and consequently change the optical transmission by an amount adequate to satisfy the definition of a switching event. In particular, changes $\gtrsim 0.3$ dB have been realized in subpicosecond times for energy densities of ~ 3 $\mu J/cm^2$ (the minimum switching energy for such a switch would be ~ 30 fJ).[3] This is equivalent to a switch utilizing independent atoms with $\sigma \cong 8\times 10^{-14}$ cm^2. In principle, as indicated by the curve in Fig. 5, the heat generated per switching operation could be low enough to permit subpicosecond switching at duty cycles approaching unity.

Another case of recent interest is the use of changes in optical absorption near a band edge caused by optical carrier generation in a semiconductor in an electric field.[4] There the change in the Franz-Keldysh effect caused by carrier screening can be quite large for low densities of optically injected carriers. For example, changes in optical density of 0.3 can be obtained for an injected carrier density of $\sim 7\times 10^{14}$ cm^{-3} in 2-μm-thick layers of GaAs. This is equivalent to cycling atoms with a cross section of 2×10^{-12} cm^2 (the minimum switching energy for such a switch would be ~ 1 fJ).

The active research at present on enhanced optical interactions in condensed matter microstructures also appears highly relevant. Those enhanced optical interactions arise from essentially the same phenomena discussed here, i.e., the use of resonances in microstructures to enhance the magnitude of the optical field at the site of the interacting atoms. Other work on enhanced optical interactions which is more difficult to explain may be due to related phenomena.[7]

A final area of interest which shows progress toward goals outlined here is the generation of extremely short optical pulses. For example, by utilizing nonlinear optical intersections in small volumes, we have recently succeeded in generating optical pulses in the femtosecond time regime. We use colliding pulse modelocking in very thin dye jets to produce stable trains of optical pulses as short as 70 fsec and nonlinear frequency broadening and pulse compression in small single mode optical fibers to obtain pulses as short as 30 fsec. The shortest of these pulses have a duration of only 14 cycles of the optical field.[5] It is unlikely that electronic devices or Josephson junction switches will approach this time regime.

ACKNOWLEDGMENTS

Special thanks are due to J. P. Gordon for many valuable discussions. Thanks are also due to A. Kiel who first introduced the author to literature on this topic and to W. B. Joyce for advice on describing heat flow in semiconductors.

---

[1]R. W. Keyes and J. A. Armstrong, Appl. Opt. 8, 2549 (1969).

[2]R. W. Keyes, Proc. IEEE 64, 740 (1975).

[3]C. V. Shank, R. L. Fork, R. F. Leheny, and J. Shah, Phys. Rev. Lett. 42, 112 (1979).

[4]R. L. Fork, C. V. Shank, B. I. Greene, F. K. Reinhart, and R. A. Logan, in *Proceeding of the Second Topical Conference on Picosecond Phenomena,* edited by C. V. Shank, R. Hochstrasser, and W. Kaiser (Springer, Berlin, 1980); Appl. Phys. Lett. 38, 104 (1981).

[5]R. L. Fork, B. I. Greene, and C. V. Shank, Appl. Phys. Lett. 38, 671 (1981); C. V. Shank, R. L. Fork, R. T. Yen, R. H. Stolen, and W. J. Tomlinson, Appl. Phys. Lett. 40, 761 (1982).

[6]R. L. Fork and D. W. Taylor, Phys. Rev. B 19, 3365 (1979).

[7]T. H. Wood, D. A. Zwemer, C. V. Shank, and J. F. Rowe, Chem. Phys. Lett. 82, 5 (1981).

[8]*Optical and Electro-optical Information Processing,* edited by J. T. Tippett, A. A. Berkowitz, L. C. Clapp, C. J. Koester, and A. Vanderbaugh (MIT Press, Cambridge, Mass., 1965).

[9]R. L. Fork, W. J. Tomlinson, and L. J. Heilos, Appl. Phys. Lett. 8, 162 (1966).

[10]S. M. McCall, H. M. Gibbs, and T. N. C. Venkatesan, Phys. Rev. Lett. 36, 1135 (1976).

[11]As an example of a situation where the independent-atom model is not adequate see, e.g., J. J. Hopfield, Phys. Rev. 112, 1555 (1958).

[12]For a discussion of one approach to the problem of optical memories see, e.g., W. J. Tomlinson, E. A. Chandross, R. L. Fork, C. A. Pryde, and A. A. Lamola, Appl. Opt. 11, 533 (1972).

[13]A. W. Lo, in *Micropower Electronics,* edited by E. Keonjian (MacMillan, New York, 1964).

[14]D. Curie, *Luminescence in Crystals* (Wiley, New York, 1963), p. 68ff.

[15]C. H. Bennett, IBM J. Res. Dev. 17, 525 (1973).

[16]The example of a laser transition having one of the largest known interaction cross sections (where the independent-atom approximation applies), used as σ_m here, is that of the $(4f^6)T_{1g}-(4f^5fd)A_{1u}$ transition in Sm^{2+} in CaF_2 at 7083 Å. There, the high symmetry $m3m$ site prevents lifting of the upper-state degeneracy. This leaves the transition narrow (0.6 cm^{-1} linewidth at 4.2 K) despite the $4f^5 5d$ character of the excited state. This leads to one of the largest cross section ($\sigma=2.5\times10^{-15}$ cm^2) for a solid-state laser transition, also one of the largest spontaneous emission rates (5×10^5 sec^{-1}) for such transitions. See, e.g., P. P. Sorokin, in *Quantum Electronics, proceedings of the Third International Congress,* edited by P. Grivet and N. Bloembergen (Columbia University Press, New York, 1964), p. 985. An example of a typical laser used in many current applications is the Nd^{3+}:YAG laser with wavelengths near 1.06 and 1.3 μm. Representative cross sections there are $10^{-19}-10^{-20}$ cm^2. See, e.g., S. Singh, R. G. Smith, and L. G. Van Uitert, Phys. Rev. B 10, 2566 (1974).

[17]L. Allen and J. H. Eberly, *Optical Resonance and Two Level Systems* (Wiley, New York, 1975), Chap. 8.

[18]E. M. Purcell, Phys. Rev. 69, 681(A) (1946). R. V. Pound, Ann. Phys. (N.Y.) 1, 24 (1957). It is also well known that a comparable inhibition of spontaneous emission occurs if the emitting atoms are confined in a microresonator tuned away from the atomic resonance. For a recent discussion of inhibition of spontaneous emission see, e.g., D. Kleppner in Phys. Rev. Lett. 47, 233 (1981).

[19]*Tables of Individual and Cumulative Terms of Poisson Distribution* (General Electric Co., New York, 1962)

[20]M. Jakob, *Heat Transfer* (Wiley, New York, 1949), Chap. 8.

[21]The assumption that the lattice phonons obey a diffusion equation is employed here. Experience with room-temperature semiconductor laser diodes suggests that these are valid assumptions at room temperature for well bonded materials. Modification of the model might, however, be required at low temperatures if the mean-free path of the lattice phonons becomes comparable to the switch dimensions.

[22]The approximate switching rates and energies typical of alternative switching systems can be obtained from current literature. A representative paper on integrated electronic devices is, P. W. Verhofsteadt, Proc. IEEE 64, 842 (1976). A representative paper on Josephson junction devices is H. H. Zappe, IEEE Trans. Magn. 13, 41 (1977).

[23]This follows directly from the fact that the net moment of N cooperating ions in a volume $\ll \lambda^3$ scales with N as $N^{1/2}$ for constant energy, and the radiative rate scales as the moment squared.

[24]C. Kittel, *Introduction to Solid-State Physics,* 3rd ed. (Wiley, New York, 1968), p. 229.

[25]See, e.g., Jagdeep Shah, R. F. Leheny, and W. Wiegman, Phys. Rev. B 16, 1577 (1977).