(42) ALKEMANDE C.T.J. - Physica, 25 (1959), 1145.

(43) As before the instantaneous intensity is represented here by the squared modulus VV^* of the analytic signal, not as the square of the real field U.

(44) MANDEL L., SUDARSHAN E.C.G. and E. WOLF - to be published.

(45) FURTH R. - Z. Phys., 50 (1928), 310.

(46) MANDEL L. - J. Opt. Soc. Amer., 51 (1961), 797 ; GABOR D. - Progr. in Optics (Ed. E.WOLF, Amsterdam, North-Holland Publishing Company, Vol.1 (1961), 133.

(47) GAMO H. - (a) Proc. Symposium on Electromagnetic Theory and Antennas, Copenhagen, June 1962 (London, Pergamon Press), In Press. (b) Proc. I.E.E.E. (In Press).

DISCUSSION

R. GLAUBER (Harward University - USA) - How can one show that the probability distribution for light from thermal sources is Gaussian ?

E. WOLF - If the field is considered classically as superposition of a large number of wave trains from independently radiating atoms, the result follows simply from the central limit theorem of probability theory. But explicit proof has been given by Van Cittert in Physica (about 1934) and more recently by Janossy, in papers published in Nuovo Cimento (about 1957 and 1959). The question was also discussed by Blanc-Lapierre e Dumontet (Revue d'Optique - 1955).

R. GLAUBER - I think you should treat the problem quantum-mechanically.

E. WOLF - I said right at the beginning of my talk that I am giving an account of the classical and semi-classical treatments only. Of course, one should try to formulate a full quantum mechanical treatment of coherence, but this may not be very easy to do. For many purposes the classical and semi classical treatments are quite good approximations and in fact have been extremely successful in predicting the results of experiments.

One should also bear in mind that the classical theory arose from an attempt to understand certain types of phenomena with light from thermal sources. Of course, as new problems arise, the theory has to be extended and this is precisely what is now being done with the help of higher order correlation functions. But my guess is that for maser light classical theories will be even more useful than for thermal light.

G. TORALDO DI FRANCIA (Italie) - Refering to your discussion of spatial coherence in the output of an optical maser, is not the answer obvious, since a single mode is selected, and so one must have coherence ?

E. WOLF - I do not think the explanation is quite that simple. For the output of a maser will never be strictly monochromatic, and so the emergent light may be partially coherent. In any case I was interested in the question of how the coherence is actually generated, and I think the answer is basically that propagation and diffraction play the essential role in reaching the high degree of space coherence in the maser output.

The Coherence Brightened Laser

R. H. DICKE

Palmer Physical Laboratory, Princeton University, Princeton, N. J.

INTRODUCTION

There are at least two reasons for giving a talk. Either the material is so new that no one has heard it, or else the material is so old that people have forgotten it. The subject of this talk falls more nearly in the second category. However, some of the questions which I shall cover have not yet appeared in print although they were discussed over ten years ago.

Historically there have been two separate and relatively unrelated origins for the concept of the laser. One of these is the familiar one, treating the laser as a fed-back amplifier, the amplification being treated as resulting from stimulated emission, the upper energy state having an excess population. The second approach treated the laser not as an amplifier, but rather as a source of spontaneous emission of radiation with the emission process taking place coherently. One simply asked for the energy states of the radiator, the radiator being all the atoms taken as a whole, such that the radiating system emitted its radiation strongly and coherently in spontaneous transitions between these energy states[1]. In principle these states could be excited without making use of the mechanism of feedback amplification, and in fact what may have been the first optical laser ever proposed an idealized laser which has not yet been realized in practice, was one of this type. It did not make use of stimulated emission and did not employ mirrors for purposes of realizing an optical feedback amplifier.

The subject of my talk will be a laser of this type, namely a laser which does not employ mirrors in order to produce feedback amplification. It should be emphasized that this type of laser is merely a theoretical model, having never been realized in practice, but the state of the art in the laser field is advancing so rapidly that I have every reason to believe that this type of laser will be produced before long. This type of laser was first discussed briefly in talk before the American Physical Society, January 22, 1953. It was also discussed at the Fourth Congress of the International Commission of Optics held in Boston in 1956[2].

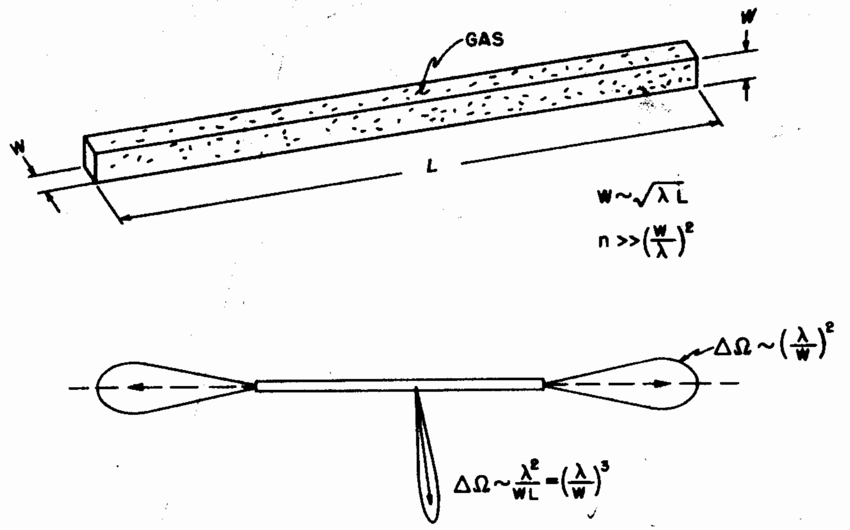
Although this paper treats the radiation process quantum mechanically, for large numbers of atoms in the radiating system the radiation process can be treated reasonably well semiclassically. The chief point at which such a semiclassical treatment, for which the oscillating electric-dipole expectation values are treated as classical radiators, is inadequate is at the start of the radiation process (for an initial state of definite energy for which all these dipoles have zero moments)[3]. While the quantum mechanical treatment of the radiation process is not essentiel, it will be used in this discussion which will rather closely follow my 1954 paper[1].

There are two separate problems connected with the generation of radiation coherently by a laser. The first problem concerns the means whereby the laser is put into an energy state for which it radiates coherently. The second problem concerns the coherent radiation process itself. The technique to be described for exciting the coherent radiation states in the laser (the coherence brightened laser) is quite different from the usual one. In fact the closest analogue is the Brown-Twist effect[4].

This method of establishing coherence in the laser I have called the "coherence brightening of the laser". This concept of coherence brightening can be understood in terms of the Brown-Twist effect by referring to Fig. 1. In Fig. 1 there is shown the type of idealized laser first discussed in 1953. There is shown a highly idealized laser of a gaseous type. This is a two level laser in which the majority of the gas molecules are initially in the excited state. It should be noted that there are no mirrors at the end of the column of gas and the functioning of the device in no way depends upon radiation being reflected back through the column. Assuming that all the atoms are initially in their excited state the total number of atoms n must satisfy the condition shown.

The phenomena of coherence brightening, the means whereby the strongly radiating coherent states of the laser are excited can be understood from the lower of the two diagrams in Fig. 1, and can be described qualitatively in terms of the Brown-Twist effect. The Brown-Twist effect is often described as a Boson condensation phenomena, whereby photons tend to cluster resulting in successive photons tending to be emitted in the same direction. On the other hand it has been shown that the same effect can alternatively be described in a different way, in terms of the angular correlation of the successive emission of photons[1]. This coherence radiation effect is quite similar to the well known nuclear physics phenomena where angular correlations between successive photons serve to give useful information about the states of the nucleus. In the optical case the angular correlation phenomena is the following : A radiating system is assumed to be initially

in an incoherent or random state for which it radiates its first photon incoherently. It can be shown that the particular direction of emission at which the first photon happened to appear is then favored for the emission of the second photon. (This is with the assumption that the various relaxation mechanisms and line broadening effects occuring in the radiator are sufficiently slow that the second photon appears before atomic motion or relaxation mechanisms disturb radiator).



SUPER-RADIANCE LASER

Fig. 1 - This is a representation of the type of idealized laser under discussion, a laser for which the excitation of "superradiant states" (see ref. 1) is accomplished by "coherence brightening", making use of the Brown-Twist effect. There are no reflecting mirrors and the directivity of the superradiant transitions results from the pencil shape of the radiator.

From an angular correlation point of view a memory of the direction of emission of the first photon is burned into the energy level structure of the radiating system, the whole system being treated as a single radiating atom, in such a way that the emission of the second photon finds this direction favored over others[1]. To put the matter in quantitative terms, for an initially incoherent radiating ensemble of large dimensions the probability of radiating a photon in a particular direction is given by the normal incoherent intensity multiplied by the total number of photons previously radiated in that direction plus 1.

In stating that the probability for emission into the same direction is increased by previous photons that have gone in the same direction, I was speaking a bit inexactly. To make it more exact the radiating system is capable of radiation into certain normal radiation modes. Two such radiation modes are shown schematically in the lower part of Fig. 1. The solid angle of these radiation modes is simply determined by the normal diffraction width of a system of radiators oscillating coherently and distributed as the atoms in the gas are distributed. It may be noted that the "end fire modes", the two normal radiation modes for which radiation leaves the ends of the pencil array of atoms, have a larger solid angle than any other normal modes. This makes the a priori probability of a photon being emitted into the "end fire mode" greater than the other a priori probabilities by a factor $\sim W/\lambda$. Thus the first photon emitted is apt to be radiated into one of the end fire modes in preference to some other mode and then because of the Boson condensation phenomena (or if you prefer the angular correlation effect mentioned above) these two end fire modes are more likely to receive the successive photons than any other mode. This results in a substantial brightening of the two end fire modes relative to the other radiation modes. This effect of the Boson condensation effect in brightening the end fire modes is the effect which I have called coherence brightening. In order to treat the coherence brightening effect, and the resulting strong coherent radiation, by this type of idealized laser it is necessary to discuss the quantum mechanical aspects of the problem with more care. It should be emphasized again that the quantum mechanical treatment is not essential in the case of a large number of radiating atoms but it is a convenient description as it can be used also to treat the very simple case of a few radiating atoms for which the semi-classical calculation gives incorrect results. It is also convenient for the discussion of photon correlation effects.

COHERENT RADIATION BY MULTIPLE ATOM SYSTEMS

A convenient and simple introduction to the problem of coherence from a quantum mechanical point of view can be seen by making reference to Fig. 2. Fig. 2 is divided into four parts, in Fig. 2-1 we have shown in a highly schematic form the basic difference between the ordinary laser (the upper part) and the coherence brightened laser. In lasers of the ordinary type the coherently oscillating strongly radiating states of the atomic system are excited by taking the radiation emitted and reflecting it back again into the gas or solid to induce new transitions. Strongly oscillating states of the radiator as a whole are induced by the strong fields acting on the radiating system. In the idealized laser shown in the lower part of the diagram relaxation mechanisms and inhomogenous broadening and doppler broadening of the line are neglected. The memory of the previously emitted electromagnetic field is burned into the radiating system rather than being sent back into the radiating system by the use of mirrors. In Fig. 1-2 is shown schematically the manner in which one treats the radiation

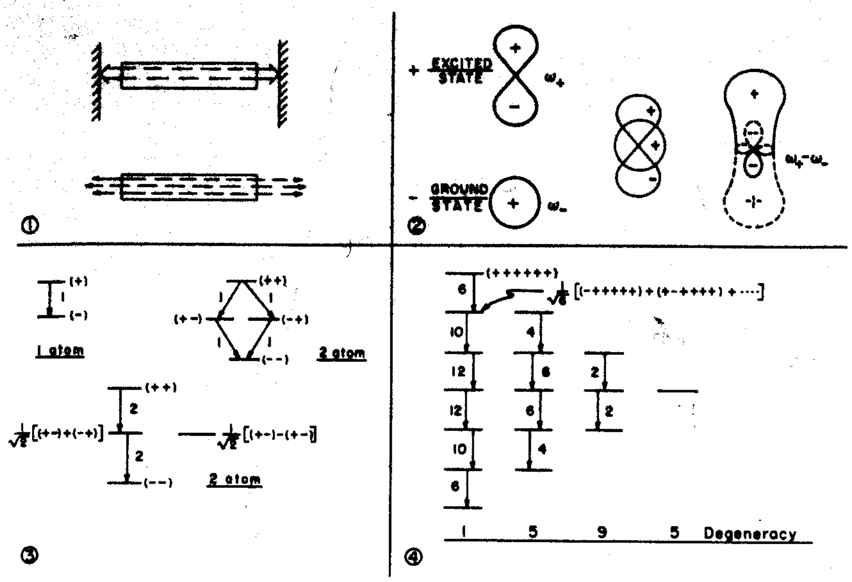


Fig. 2 - This figure is in 4 parts. Fig. 2-1 shows the structural difference between an ordinary laser and a coherence brightened laser. Fig. 2-2 shows schematically the oscillating charge density expectation values resulting from the excitation of an atom into superposition states. Such atomic superposition states are essential to the treatment of the coherent radiating system semi-classically. Fig. 2-3 shows the energy-level diagram of a two-atom radiator. These energy levels are essential concepts if the radiation process is to be treated quantum mechanically. Fig. 2-4 shows the energy-level diagram for a 6 atom radiator.

process semi-classically. The wave functions of the ground state and excited state are shown schematically, also the wave function when the atom is partially excited and partially in its ground state. One notes that in the case of the superposition of the energy states there is an oscillating probability amplitude for the charge resulting in the charge probability distribution oscillating back and forth in the vertical direction as shown in the right hand part of this figure. This semi-classical treatment describes coherence effects by having definite phase relations between the phases of the oscillating probability distributions of different atoms. In other words the coherence effects are described by properly adjusting the phases of these oscillating charge distributions to cause them to cooperate in their radiation processes.

The treatment of the coherence effect quantum mechanically is quite different and is shown schematically for a case of a two atoms radiating system in Fig. 1-3. In the upper left hand part of part 3 one sees schematically the notation for designating excited and ground states for a two level atom. The energy levels and labeling of the quantum mechanical states of a two atoms system is shown in the upper right hand part of the diagram. It may be noted from this diagram that from the upper energy state a photon can be emitted in two different ways falling into one of the two possible intermediate excited states and then, from each of these excited states a system can drop to its ground state (--) again emitting photons. Actually, because of the symmetrical coupling to the electromagnetic field, these transitions are not what actually occurs. An atom jumps from the top excited state (+ +) into the state which is shown in the lower part of this diagram, a state which is a symmetric combination of the (+-) and (- +) states. By analogy with the familiar system of 2 spin 1/2 particles, one could call this a triplet state and the corresponding antisymmetric state, to which a transition does not occur, the singlet one. It should be emphasized that it is only when the two atoms are very close together that transitions between the singlet and triplet system is forbidden. The problem of how emission takes place when the atoms are widely spaced will be discussed later.

There are several points that are worth emphasizing at this particular point. First, of the two intermediately excited states of the two atoms system, the triplet state emits with a probability which is twice the normal incoherent one and the singlet state does not emit at all. It may be noted that if the initial state of the two atoms system is one for which the first atom is excited and the second atom definitely not, this is a superposition of the triplet and singlet energy levels such that there is a probability of 1/2 that the atom emits and a probability 1/2 that it does not. From the standpoint of coherence one could say that in its highest energy state (the + + state) the two atoms system emits incoherently inasmuch as it emits at its normal incoherent radiation rate. However, the second photon is emitted coherently and the transition probability is greater by a factor of 2 than the incoherent probability, the transition probability in a single isolated atom.

To come to Fig. 2-4, the analogous energy levels and their transition probabilities are shown for the case of a system of six atoms closely spaced. The uppermost energy level is the level for which all six atoms are excited and of course the lowest level is one for which none of the atoms are excited. The two most strongly radiating states of the six atoms system are the ones for which the transition probability is 12 times that of a single isolated excited atom. It should be noted that although only 3 of the atoms are excited the radiation rate in this particular case is twice as great as if all the atoms had been excited. On the other hand the greatest radiation intensity anomaly occurs in the transition to the ground state. In this case the radiation rate is 6 times the normal incoherent rate for the emission of a photon. In considering Fig. 2, parts 3 and 4, it should be emphasized that the energy level diagrams shown refer to energy levels of the radiating system as a whole, not the individual atoms.

Referring again to Fig. 2-3, the upper right hand part, the energy levels (+ -) and (- +) are degenerate and may as a result be superposed arbitrarily to give new possible stationary states. The triplet and singlet combinations shown in the lower part of this diagram are convenient superpositions to use. The coupling to the electromagnetic field is symmetric under an exchange of atomic labels and hence transitions take place wholey in the triplet system, with no triplet to singlet transitions occuring.

COHERENCE IN LARGE RADIATING SYSTEMS

The assumption that the radiating system occupies a volume very small compared with a wave length cubed, or more precisely that the maximum dimension of the radiating system is small compared with the wave length, is a very unrealistic and difficult condition to achieve in an optical radiator. Of more interest for optical coherence problems is the question of coherence in the two atom radiator having a separation between atoms large compared with the wave length. The energy level diagram shown on the left hand side of Fig. 3 refers to the energy levels of a two atom radiating system, the atoms being separated by 2 1/2 wave lengths. It should be noted that the two intermediate energy levels are again chosen to be the symmetric and antisymmetric combination of the basic energy states, these being the energy levels which we had previously designated as triplet and singlet. It will become evident from the discussion below that these are not the only possible choices to make for these energy levels, and that in fact any combination of the (+ -) and (- +) states, with equal probability contributions from each of these two states, would be a possible choice.

Because of the relatively large separation between the atoms in this radiating system, it is no longer true that transitions from the triplet energy state to the singlet state is forbidden. Thus if the system starts out with both atoms excited, the first photon can be emitted by making transition either to the singlet or antisymmetric state (A) or to the symmetric triplet state (S). As a matter of fact, the first photon could be emitted by making a transition to any superposition (of these two states) such that the excitation is with equal probability assigned to each atom.

Let us assume for definiteness that the system is in the intermediate symmetric state. The photon is emitted in such a way as to cause the radiator to jump into the (- -) symmetric state. It is found upon calculation that the probability distribution pattern for the emission of this photon is the one shown dotted in the right hand part of this diagram. This radiation pattern is identical with the classical entenna pattern of a two dipole antenna. This pattern gives the probability distribution for the emission of the photon, if the transition is from one symmetric state to another.

Alternatively the initial state might have been the antisymmetric one. In this case the only possible transition is to the symmetric lowest energy state and the radiation pattern (probability distribution pattern) is shown as the solid curve.

The problem of the angular correlation of two successive photons can now be discussed. The initial state is now the symmetric (+ +) state. It may be noted that if the first photon emitted is detected moving in a certain direction, then we can be sure that this particular direction is not one of the nodal directions of the radiation pattern, a direction for which the probability of emission is zero. For example, if the first photon is observed to be emitted at right angles to the line joining the two atoms, we can be certain that the transition was not into the antisymmetric state for which the radiation pattern shows a node in this particular direction. If the transition did not occur to the anty-symmetric state it must have occured to the symmetric state. Consequently for this particular case the first photon is emitted into a di-

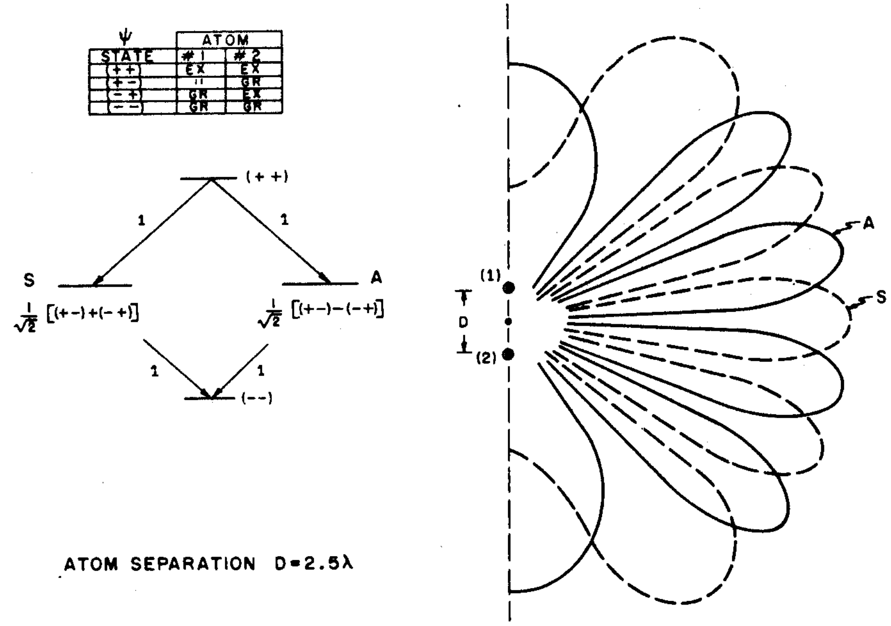


Fig. 3 - This shows the energy level diagram, transition probabilities, and radiation patterns for a two-atom system when the 2 atoms are separated by 2.5 wave lengths.

rection which is the center of one of the radiation lobes of the symmetric radiation pattern. It might be inferred from this that the first photon could only go into one of a few possible directions, the directions constituting the centers of the radiation lobes of the symmetric and antisymmetric transitions shown in the right hand side of Fig. 3. This, however, is a misinterpretation. It should be remembered that the choice of the two intermediate stationary states shown in the left hand side of this diagram was an arbitrary one and that in particular the left hand energy level might have been designated.

$$\frac{1}{\sqrt{2}}[(+\,-) + e^{i\delta}\,(-\,+)]$$

in which case the orthogonal right hand energy state would be

$$\frac{1}{\sqrt{2}}[(+\,-) - e^{i\delta}\,(-\,+)]$$

It must be stated that the first photon emitted can be emitted in any direction compatible with the directivity of the individual atom radiation pattern, but that its direction of emission determines the intermediate energy state in which the radiating system is placed. In every case this first photon is emitted into the center of one of the lobes of the radiation pattern corresponding to this particular energy state. It follows therefore that knowing the direction of emission of the first photon one can predict the probability distribution for the radiation of the second photon. It also follows that in this probability distribution pattern there are directions for which the second photon is absolutely forbidden. This is a quantum mechanical effect having no classical analogue. If the corresponding correlation problem is considered for classical radiators arbitrarily phased, it is found that the cross-correlation pattern shows similar lobe structure but that the lobes are not so sharply defined, there being no forbidden directions.

One interesting and somewhat paradoxical aspect of the correlation and coherence problem being discussed is the fact that the two radiating atoms could be extremely far apart, many, many wave lengths, and still exhibit this correlation effect. One might naively wonder with such a radiating system, initially in a state for which both atoms are excited, how the one atom would ever know about the existence of the other. It is only because of the presence of the 2nd atom that the radiation distribution pattern for the emission of the second photon depends upon the direction of emission of the first. It should be remembered however that both atoms are coupled to the same electromagnetic field. In the process of emitting the first photon, this common coupling results in the excitation of correlation states between the two atoms.

We are now in a position where we can discuss the coherent radiation by a many atom system occupying dimensions large compared

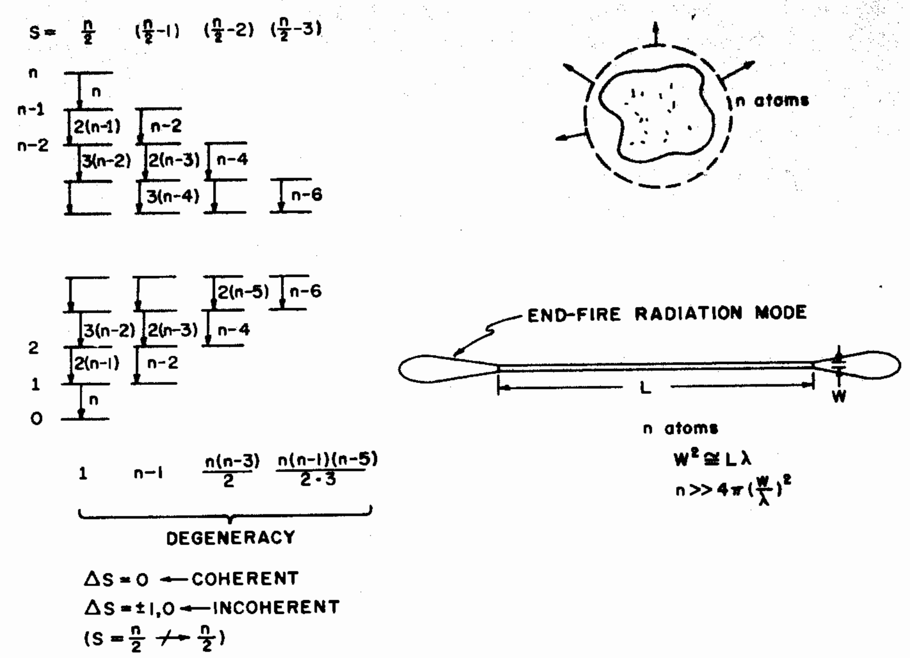


Fig. 4 - Shows schematically the energy level diagram of an n atoms radiating system, the transition probabilities referring to radiation into some one normal mode of the electromagnetic field. For an amorphous radiating system, such as illustrated in the upper right hand corner, there is no one radiation mode singled out for particularly strong coupling. If, however, the radiator normal modes and the transition probabilities (and energy states) are defined as representing coupling to one of the end fire modes.

with the wave length. Consider Fig. 4. In the treatment of radiation problems quantum mechanically, it is customary to expand the electromagnetic field in plane wave modes and to consider the coupling between the radiating system and these various plane wave radiation oscillators. This, however, is not a particularly convenient expansion for the discussion of coherence effects. For an irregularly shaped radiating system, such as the one shown in the upper right hand part of Fig. 4, it is more convenient to expand the electromagnetic field in spherical waves about the center of the radiating system. Spherical waves of large spherical harmonic index l do not couple to the radiating system. A spherical standing wave of sufficiently large l has a substantially zero amplitude over the whole of the radiating system. Thus one finds that he is dealing with a coupling of only a finite number of electromagnetic modes to the radiating system.

For an irregularly shaped radiator, such as the one shown in the upper right hand corner of Fig. 4, there is no unusually strong coupling to any one electromagnetic spherical standing wave and the coherence brightening effect discussed in the introduction does not occur. If, however, the radiating system is in the form of a long thin pencil such as shown in the lower right hand part of Fig. 4 the expansion in spherical waves of the usual spherical harmonic type is not the most convenient. Instead it is more convenient to chose a set of orthogonal spherical waves based on the normal mode radiation patterns of a system of simple harmonic oscillators distributed spatially along a pencil such as shown. These modes are so defined that the two end fire modes are included. In fact the end fire radiation modes have the largest solid angle of all these orthogonal modes. The coherence energy states of the atom system are defined with respect to transitions leading to the emission of photons into an end fire mode. These energy states and transition probabilities are illustrated in the left hand side of Fig. 4.

Of course it should be remarked that the transition probabilities shown in the left hand side of Fig. 4 between these various energy states are not the only radiation transitions which can occur. We shall call these the coherent transitions, however, in that the various atoms are radiating cooperatively, lead to the emission of photons into the end fire radiation mode in which we are interested. To illustrate the kind of transitions which can occur when the radiation is not emitted coherently we turn to Fig. 5 here the energy level diagram is shown for the

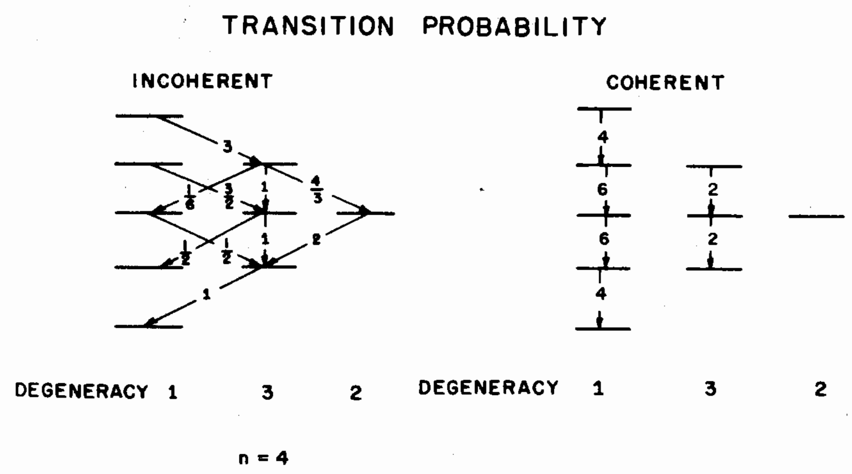


Fig. 5 - In this figure both the coherent transition probabilities (for coupling to the chosen radiation oscillator) and the incoherent transition probabilities (transitions to all the other radiation modes assumed large in number) are shown for a four atom radiator.

simple case of 4 atoms in a large array. The transition rates shown in the right hand part of Fig. 5 are the coherence radiation rates associated with transitions in which photons are emitted into the particular radiation oscillator mode which has been selected for special consideration. On the other hand the transitions shown in the left hand side of this diagram are indicative of all the other types of transitions which can occur. What these probability rates represent is a sum over all the other types of transitions which can occur assuming that there is a very large number of other radiation modes which can be excited.

Figs. 6 and 7 show the corresponding transitions for the more complicated case of a radiating system containing 6 atoms. If we think of these six atoms as being distributed along a pencil such as shown in Fig. 1, then the transition probabilities shown in Fig. 6 refer to transitions in which the photon is emitted into the end fire radiation mode. The transition rates shown in Fig. 6 refer to transition probabilities in which the emission into all the other possible radiation states are summed.

It is necessary to say a word about the normalization of the transition probabilities illustrated in Figs. 5 et 6. Ignoring the directivity of the radiation patterns of the individual atoms, that is considering the individual radiating atoms as radiating isotropically, the coherent transition rates in Fig. 6 must be multiplied by P, where P is the effective radiation solid angle of the end fire mode (divided by 4π). These transitions probabilities then appear in units of the transition probability of a single isolated excited atom. In similar fashion the incoherent transition probabilities, Fig. 7, are to be multiplied $\frac{1}{5}(1 - P)$. It is implicitely assumed that there are many radiation modes to which the radiator can couple. It should be remarked that the various transition rates shown in these figures are to be interpreted as rates out of the initial state rather than rates into the final state, there being a difference in degeneracy.

A completely incoherent excitation of the radiator at a particular energy level is equivalent to exciting with equal probability all the stationary states of a particular energy. Making use of the transition rates shown in Figs. 4, 5, and 7 it is easy to verify that, for the radiator in such an incoherent state, the first photon is emitted with equal probability in all directions. It is also easy to verify that if this first photon is emitted in the end fire radiation mode, the second photon is emitted into the same mode with a probability which is twice the incoherent rate. More generally, the probability of the s^{th} photon being emitted into the end fire mode is given by the incoherent transition probability multiplied by the total number of photons previously emitted into this mode plus 1.

An approximate expression for the coherence brightening factor has been computed and is plotted in Fig. 8. We define the coherence

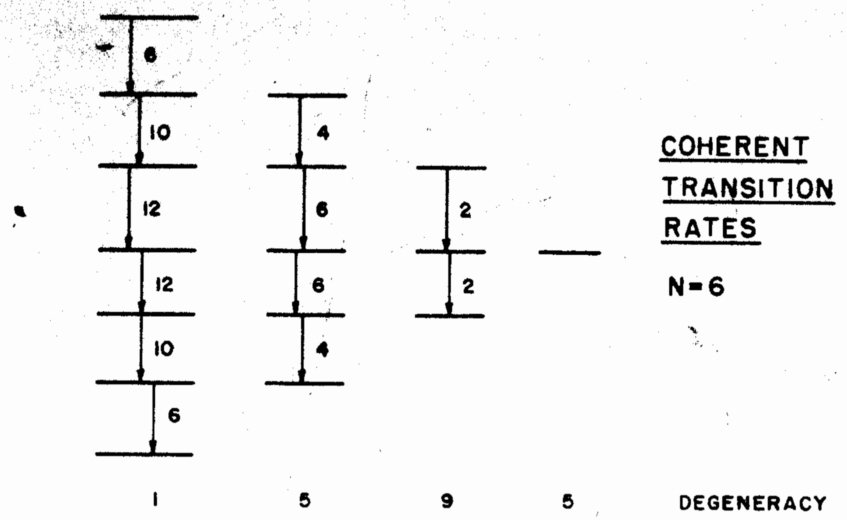


Fig. 6 - Coherent transition probabilities for a 6 atom radiator are given. (See text for normalization).

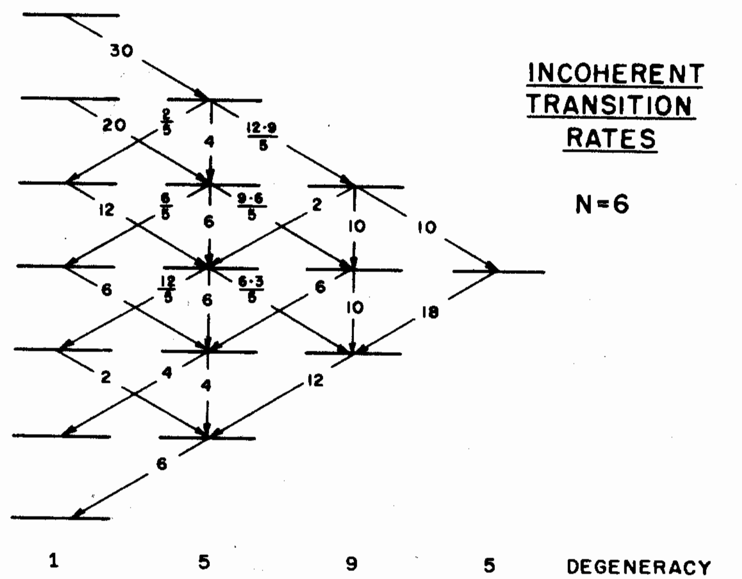


Fig. 7 - Incoherent transition probabilities for a 6 atom system coupling to many electromagnetic normal modes. (See text for normalization).

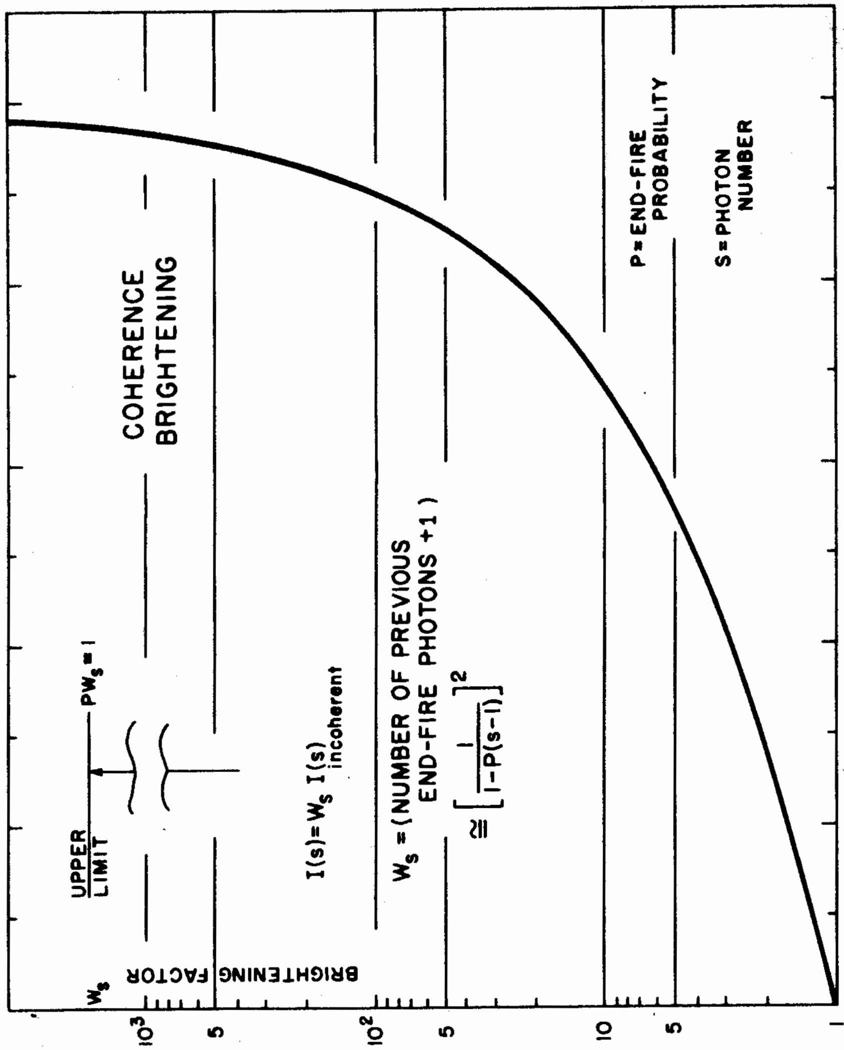


Fig. 8 - Coherence brightening curve. The ordinate gives the factor by which the normal incoherent radiation rate into the prefered mode must be multiplied to obtain the radiation rate. The absissa is essentially the number of previously emitted photons which would have been emitted into this prefered mode if the Boson condensation effect were absent, namely the total number of previously emitted photons multiplied by the a priori probability of radiation into the prefered mode.

brightening factor in the following way : If the radiating pencil of atoms is initially excited incoherently to a particular energy, its radiation rate into the end fire mode after s photons are emitted is designated by $I(s) = W_s\, I_{incoherently}(s)$. As a result of coherence in the radiating system, the radiation rate into the end fire mode is greater than the incoherent rate for the same total energy of excitation. The factor by which the incoherent rate must be multiplied in order to obtain the intensity of radiation into the end fire mode is designated by W called the coherence brightening factor. In Fig. 8 the coherence brightening factor is plotted as a function of the factor P (s - 1), where P again means the a priori probability of incoherent radiation being emitted in the end fire mode and s represents the s^{th} photon emitted by the radiator after starting out radiating incoherently. The upper limit shown is an upper limit on the validity of the calculation assuming that one started with the radiating system excited to its highest energy state. If the initial incoherent state of the radiator is not of this high a level of excitation, the coherence brightening takes place on exactly the same way but the calculation becomes invalid sooner. Stated in other words, the brightening after a number of photons have been emitted depends only on the number of photons emitted and not on the initial level of excitation of the incoherent radiation state. It should be noted, however, that the brightening factor could be very large, perhaps 10^6, without the normal condition of a laser being satisfied with respect to its initial incoherent state. Namely, it is not necessary for the initial incoherent state to be one for which the upper energy level has the higher population for coherence brightening to take place. However, it should be remarked that if this laser condition is not satisfied, coherence brightening can not become so great as to result in the bulk of the energy being emitted in the end fire mode. In other words the coherence brightening factor can be large (without an initially inverted population) only if the solid angle of the end fire mode is small.

If the populations are initially inverted, the upper atomic energy state being most populated, the coherence brightening can occur until the rod starts to radiate as a true laser, the bulk of the radiation appearing in the end fire modes.

In Fig. 9 the coherence brightening factor is plotted for a numerical example of an idealized laser containing 10^4 atoms all initially in their excited states and arranged in a long pencil array having a shape such that the a priori probability P for radiating into the end fire mode is 10^{-3}. The absissa in this plot is the total number of photons emitted after having started with this highest excitation state of the radiator. The uppermost curve shows the end fire intensity computed as a function of the number of photons previously radiated. It may be noted that the end fire intensity starts out at the normal incoherent rate of 10^4 x the radiation rate of 1 atom, simply because there are 10^4 atoms initially excited. It then rises to by something like a factor of 100 by means of the coherence brightening effect. The

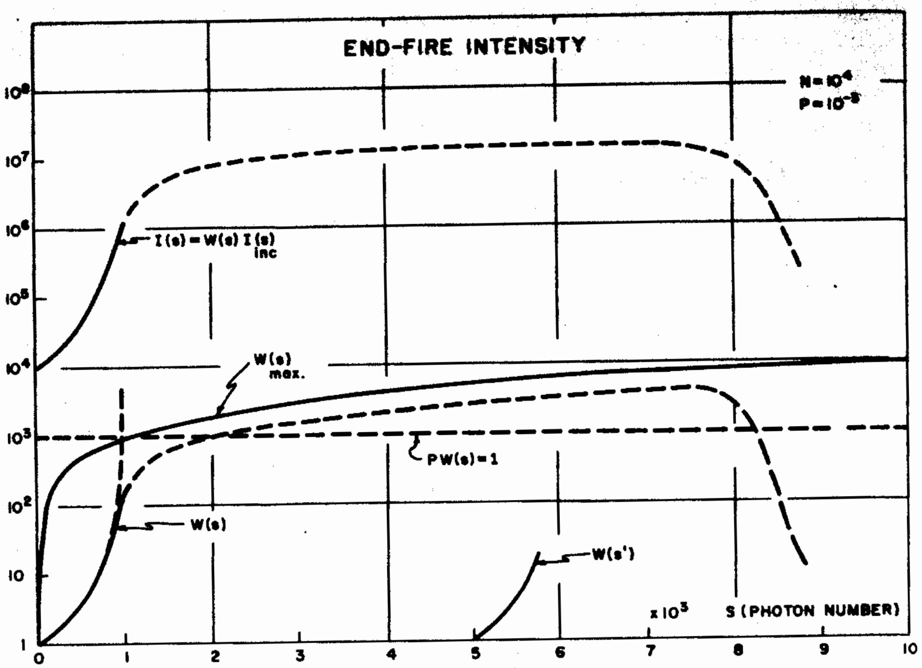


Fig. 9 - Shows the brightening and lasing of an idealized laser with an end fire a priori probability of 10^{-3} and containing 10^4 atoms all initially in their excited states. The solid curve gives the maximum brightening factor possible with a 10^4 atom system. The absissa is the number of previously emitted photons. The curve W(s) gives the brightening factor starting initially in the state with all atoms excited. The dotted portion of the curve is calculated only as a rough approximation. The solid portion is a better approximation. The curve W(s') shows the same brightening if the initial incoherent state is one for which only half the atoms are excited.

coherence brightening then levels off at about 10^7, a factor of 1 000 times the initial incoherent rate and the rod radiates as a true laser. the bulk of the energy being channeled into the end fire mode. After a total of something like 80% of the energy has been emitted the intensity falls off rapidly. It should be noted that this idealized laser continues to radiate coherently long after the lower energy level has a population greater than the upper.

The curve shown in the lower part of Fig. 9 are coherence brightening factors. The uppermost solid curve is the maximum brightening factor possible with a system having 10^4 excited atoms initially. This curve is easily computed from the transition probabilities shown in the left hand column of the energy level diagram of Fig. 4. The curve below this maximum brightening factor is the curve followed by the laser of the type under discussion. It first rises rapidly due to

the coherence brightening associated with photon angular correlation until the brightening factor reaches roughly a 100, the curve then levels off staying below the maximum brightening factor continuing to rise until roughly 80% of the photons have been emitted after which it falls rapidly.

Also shown in Fig. 9 is the short curve W(s') representing the coherence brightening which would occur if the initial incoherent state of the radiator had been one for which half of the atoms were excited and half were in their ground states. If should be noted that in this case the brightening occurs in the same way the curve rising just as rapidly, but that the calculation becomes invalid sooner and the brightening factor cannot rise to nearly as great a value as if it had started in the highly excited state for which all the atoms were initially excited.

The above discussion has been without the benefit (or hinderance) of a formal mathematical development. However, the most important parts of this were long ago published[1]. The curve plotted in Fig. 8 is only an approximation, but a quite good one if $W_s << \frac{1}{P}$ and $P << 1$, assuming that the initial state of the radiator is one of maximum excitation.

While this discussion is directed to an idealized laser, for which relaxation and line breadth is due to radiation coupling, the day appears to be near when the tremendous enhancement of radiation coupling (because of coherence) will cause it to be the dominant line broadening effect, other effects becoming negligeable. Under these conditions this mode of lasing becomes not only possible but likely.

A laser of this type, if it could be produced, would be characterized by an unusually short and intense light burst. The main part of the optical pulse length might be shorter than 10^{-13} seconds. In 1953, the words "maser" and "laser" having not yet appeared, I called this type of device an "optical bomb". This may still be the best name, because if the pulse shortened to this extent a new class of non-linear effects, not discussed above, should occur and these effects have as their closest analogy the generation of a shock wave in an explosive.

If a short optical pulse were to be sent propogating along a pencil array of atoms, all in their excited states, it would be expected that the pulse, if intense enough, would dump the energy in each atom into the wave front (the dumping being thought of as the effect of a 180° pulse applied to the atom). A calculation has shown that the wave intensity would increase and the pulse would shorten because of the non-linearity of the polarization response to a short transient exciting pulse. The shortening can be seen qualitatively from the fact that as the energy in the wave front increases the length of the pulse must decrease to preserve its 180° character.

Such an optical shock wave would be bery similar to the accoustic shock wave progating through an explosive and such a laser would indeed be an "optical bomb".

DISCUSSION AND SUMMARY

In part the distinction which has been made here between a stimulated-emission laser and a coherence brightening laser is only a matter of semantics. It was pointed out that if a coherence brightened laser brightens enough, the radiation process can be treated as the effect of an optical shock wave traversing the lenght of the pencil, this short and intense optical pulse dumping most of the energy stored in excited atoms. The condition to be satisfied if the laser is to brighten this much is that

$$n >> \frac{C W^2 \Delta\nu}{\lambda^2 L (\Delta\nu_{rad})^2} \sim \frac{C \Delta\nu}{\lambda (\Delta\nu_{rad})^2}$$

where n is the number of atoms, all initially excited ; $\Delta\nu$ is the incoherent line breadth including inhomogenous broadening, doppler broadening and relaxation broadening in addition to radiation broadening. $\Delta\nu_{rad}$ is the radiation line breadth. It should be noted, however, that if the laser brightens this much that most convenient theoretical model may be one for which the atoms are again treated as individual radiators with oscillating charge distributions. The concept of stimulated emission is not quite adequate because the 180° pulse inverts the state populations and the lasing does not stop at population equality in the two states.

Even if the coherence brightened laser does not brighten to this extent, there is a sense in which it can be called a stimulated emission laser. It should be noted that the excitation of energy states representing correlated motions in the various atoms of the radiator is through the interaction with a common electromagnetic field. We may think of the radiation reaction acting upon the various atoms to induce transitions into correlation states of the radiating system.

Conversely, we can, if we wish, consider the ordinary mirror system laser to be a coherence brightened laser. This interpretation depends upon the treatment of the mirrors as part of the radiating system. The mirrors serve to increase markedly the coupling to the end fire mode of the electromagnetic field. Thus P is increased and the number of excited atoms required for lasing is decreased.

Another possible interpretation of the reflecting mirrors is to consider them part of the electromagnetic system. As such they serve to increase the coupling P of the one normal radiation mode more than the others, again leading to enhanced coherence brightening through the Brown-Twist effect. This was a type of model which I had in mind when I added the mirrors to my proposed infra-red laser[5].

There is a somewhat paradoxical aspect to coherence brightening, an aspect requiring some discussion. It should be noted that for $P << 1$ and an initial incoherent state of the radiator, with the lower state population greater than the upper, substantial coherence brightening can take place but not to such an extent as to result in lasing. It might be asked if the increased organization of the radiator, implicit in this brightening, is compatible with thermodynamic considerations. There is no paradox if it be noted that the radiation emitted into the many radiation modes of the electromagnetic field is roughly equivalent to the flow of heat from a hot source (radiator) into a receiver at absolute zero (the electromagnetic field). This constitutes a heat engine (not in thermodynamic equilibrium) and the available work can be used to organize the radiator. Stated in other words, the decrease in entropy of the radiator is less than the increase of the entropy of the radiation field.

To summarize : The coherence brightening of the mirrorless laser by means of the Brown-Twist effect (or photon correlation effect[1]) is a possibly interesting technique for the future. It is also an interesting alternative description of an ordinary mirrored laser. The mirror-less laser should be capable in principle of generating extremely short pulses. However, there are formidable practical problems. In order to achieve the high excitation of the initial state, something equivalent to a Q switch, such as a detuning technique[5], would probably be needed Pulses less than 10^{-13} seconds long seem to be possible, at least in principle, - perhaps someday in practice !

REFERENCES

(1) R.H. DICKE - Coherence in spontaneous radiation processes, Phys. Rev. *93*, 99 (1954).

(2) R.H. DICKE - Coherence and the quantum, Jour. Opt. Soc. Amer. *47*, 527 (1957).

(3) The treatment of the radiation process semi-classically is an elementary generalization of Bloch's treatement of radiation by a system of nuclear spins.

(4) R. HANBURY BROWN - R.Q. Twist Nature *178*, 1447 (1956) (see also E.M. Purcell Nature *178*, 1449 (1956)).

(5) U.S. PAT - No. 2,851,652, filed 5/21/56, issued 9/9/58.

DISCUSSION

N. BLOEMBERGEN (Harvard University - USA) - Comment on nomenclature : a superradiant state is one in which an expectation value of an off-diagonal element of the density matrix exists.

A maser state is one in which a diagonal element of a state with higher energy has a larger expectation value than a diagonal element belonging to a state of lower energy.

Superradiant states have been known in magnetic resonance long before the term "superradiant" was introduced. A 90° pulse in magnetic resonance creates a superradiant state. An 180° pulse creates a maser state and a 135° pulse creates a mixture.

B. SENITZKY (TRG Inc., New-York - USA) - Although the states described by Prof. BLOEMBERGEN and the superradiant states of DICKE have similarities due to the correlation between the oscillations of the individual molecules, there is a subtle but important difference the superradiant states are ernegy states, and the phase of the output radiation is unpredictable, while states produced by a 90° pulse consists of a superposition of energy states of each molecule, and the phase of the radiation is predictable (it is determined by the activating pulse).

Quantum Noise in Communication Channels

J. P. GORDON*
*University of California, San Diego, La Jolla, California.

I - INTRODUCTION

It is too bad that Professor Gabor could not be here today, because it was he who coined the term "quantum noise"[1], and he did it long before the invention of the optical maser. Thus, he should by rights have the first place on the rostrum today.

I would like to discuss those aspects of quantum noise which are likely to be of importance to communications systems. Now we all have some more or less distinct notion of what we think noise is ; in fact, it might be defined very loosely as that part of our measurement we would most like to be rid of. A more proper definition might be as follows : noise is that part of a measurement which is not a signal, and which cannot be predicted in terms of our knowledge of the system in question at the time of the measurement. On this basis, even the zero error of a meter is a form of noise until it is measured. Thus, any part of a measurement which is not the signal, and which has statistically a finite mean square deviation from its expected value at the time of the measurement, may properly be termed noise. This conception of the meaning of the term noise is consistent with the fundamental ideas of information theory, and with it, we can go on to a fruitful discussion of our main subject - quantum noise.

II - PROPERTIES OF THE SYSTEM

To get on with our problemn we would like to discuss rather idealized infra-red or optical communications systems, for which the following properties are assumed :

First, the transmission medium passes only a single transverse field mode ; that is, the polarization and distribution of the field over

---

*On leave from Bell Telephone Laboratories, Murray Hill, New Jersey.

QUANTUM ELECTRONICS

proceedings of
the third international congress

ÉLECTRONIQUE QUANTIQUE

comptes-rendus de la
3e conférence internationale

PARIS

P. GRIVET
Professor, Paris University

N. BLOEMBERGEN
Professor, Harvard University

1

DUNOD ÉDITEUR
PARIS

COLUMBIA UNIVERSITY PRESS
NEW YORK

1964