Discharge-pumped cw gas lasers utilizing "dressed-atom" gain media

P. P. Sorokin,[1] J. H. Glownia,[2] and R. T. Hodgson[3]
[1]*IBM Research Division, Yorktown Heights, New York 10598-0218, USA*
[2]*MS G756, Los Alamos National Laboratory, Los Alamos, New Mexico 87545-1663, USA*
[3]*822 Pinesbridge Road, Ossining, New York 10562, USA*

(Received 28 April 2004; revised manuscript received 17 November 2004; published 12 May 2005)

The possibility of realizing an efficient gaseous laser-beam-generating medium that utilizes Λ-type coherently phased (i.e., "dressed") atoms for the active laser species, but that does not inherently require the use of external laser beams for pumping, is explored. Specifically, it is investigated if multiphoton stimulated hyper-Raman scattering (SHRS) processes driven by fluorescence radiation generated in a continuous electrical discharge present within the vapor-containing cell could produce continuous-wave (cw) optical gain at the Λ-atom resonance frequencies ω_o and ω_o'. It is deduced that such gain could result from n-photon $(n \geqslant 4)$ SHRS processes *only* if absorption of fluorescence pump light occurs in the first three transitions of the n-photon sequence representing the process unit step. Estimates of the amount of optical gain that could be produced in such a system indicate that it should be sufficient to allow multiwatt cw laser operation to occur on one set of Λ transitions connecting levels in a "double-Λ" structure, with the pump light being discharge-produced fluorescence centered about the transitions of the other Λ pair. However, to initiate operation of such a device would require injection into the laser optical cavity of intense "starter" laser pulses at both lasing frequencies. What should be an optimal experimental configuration for determining feasibility of the proposed laser device is described. In the suggested configuration, Cs-atom $6S_{1/2}$-$6P_{1/2}$ transitions form the double-Λ structure.

DOI: 10.1103/PhysRevA.71.053807 PACS number(s): 42.50.Gy, 42.65.Dr, 42.65.An, 42.50.Hz

I. INTRODUCTION

Over the past fifteen years or so, many theoretical and experimental studies have shown that radically new pathways for efficiently generating laser radiation can be accessed if use is made of coherently phased (i.e., "dressed") atoms and molecules for the active laser species [1]. An illustration of this statement is provided by a recently published experimental study [2]. In Ref. [2], copropagation in ^{208}Pb vapor of three laser pulses (with Rabi frequencies Ω_c, Ω_p, and Ω_e), each resonant with a separate allowed transition in a double-Λ configuration, resulted in efficient parametric generation of a co-propagating fourth laser pulse Ω_h, with the frequency ω_h of the latter being that of the remaining transition in the double-Λ level structure. This generation scheme embodies several recently discovered physical principles that are not active in conventional four-wave mixing experiments. To begin with, here the synchronously applied "strong" laser pulses Ω_c and Ω_p, acting on a pair of transitions that share a common upper level, coherently phase the atoms of the vapor, driving each atom into a superposition dark state which becomes nonabsorbing at the frequencies ω_c and ω_p of the two applied pulses, thereby allowing the latter to propagate orders of magnitude further into the vapor than if the atoms were not coherently phased. This establishment of electromagnetically induced transparency (EIT) also creates an atomic coherence ρ_{12} having an absolute value close to $\frac{1}{2}$, the maximum value theoretically possible. This large atomic coherence, in turn, acts as a local oscillator that can beat with other copropagating laser pulses, such as the applied pulse at ω_e, producing sum and difference frequencies. In this case, it is light at the sum frequency $\omega_h = (\omega_p - \omega_c) + \omega_e$ that is exactly resonant and that becomes efficiently generated. Were the atoms not coherently phased, the generated light at ω_h would be very strongly attenuated. Here, however, with the effects of quantum interference and atomic coherence playing important roles, a remarkable redistribution of intensities and phases of the pulses at ω_e and ω_h automatically occurs, resulting in the additional establishment of EIT on both transitions. All four laser pulses then propagate stably together as "matched pulses" in a completely loss-free manner, with the asymptotically attained Rabi frequencies Ω_e and Ω_h satisfying the condition $\Omega_e/\Omega_h = \Omega_c/\Omega_p$. Having all four laser beams exactly resonant, of course, allows access to nonlinear mixing susceptibilities that are orders of magnitude greater than are available in conventional four-wave mixing experiments. In Ref. [2], this enabled significant $\Omega_e \rightarrow \Omega_h$ photon conversion to occur over very short interaction lengths, and contributed importantly to the high efficiency observed for this process. Additionally, when this new approach to laser beam generation is followed, it no longer becomes necessary to seek ways to phase match the beams, since the latter occurs automatically when all the beams are resonant.

In the scheme employed in Ref. [2], and (to our knowledge) in all other published schemes that have focused upon the use of coherently phased atoms or molecules for laser beam generation, one or more externally applied laser beams are required both to coherently phase the active species, and to supply photons that can be converted to those of an output beam generated at another frequency. This statement, of course, does not hold for the vast majority of standard laser types, i.e., those requiring that population inversions be present on lasing transitions (but not requiring that the active species be coherently phased). One can therefore reasonably

 ©2005 The American Physical Society

inquire whether it might also be possible to realize a laser that is based upon coherently phased atoms or molecules, but that is pumped in some manner with incoherent energy, so that application of external laser beams is not intrinsically required to power the system. In the present paper the authors attempt to partially answer this question by exploring in a general way whether there exist photonic mechanisms which could directly convert "unphased" atomic fluorescence light produced in a low-pressure continuous gaseous electrical discharge into "phased" laser light, this conversion occurring on coherently-phased atoms present in the discharge.

The method here adopted for determining whether or not such a discharge-pumped, coherently-phased-atom laser could ever be realized is based upon analysis of a specific model that should optimally represent such a system. The model here utilized can be roughly described as follows. The source of pumping energy is envisioned to be a continuous electrical discharge occurring in a low-pressure ($\sim$0.1–1 Torr) atomic vapor contained within an optical cell of length, say, between 1 and 2 meters. The electrical discharge is assumed to run the length of the cell, occupying most of its volume and producing throughout this volume intense atomic line fluorescence. At present, alkali metal vapors appear to be the best candidates for the laser idea here being explored. For these, the discharge-produced atomic line fluorescence would be mostly concentrated in the D_1 and D_2 lines. In the model here employed the optical cell itself is incorporated into an aligned optical laser cavity, the mirrors of which are assumed to be almost totally reflective at the frequencies of the beams that the laser would be expected to generate. Output coupling losses are assumed to be on the order of one percent. Utilization of a ring cavity configuration is conceptually easiest to visualize. One next postulates in the model that two, fairly intense, continuous-wave (cw), highly monochromatic, laser beams Ω and Ω' are axially copropagating through the cell in a low-order transverse optical cavity mode, these beams representing the coherent laser light that is generated by the system. (In the usual manner, Ω and Ω' are here the angular Rabi frequencies of the beams, with $\omega_o = 2\pi\nu_o$ and $\omega_o' = 2\pi\nu_o'$ being the actual angular laser frequencies.) The transverse dimension of each of these beams within the optical cell is assumed to be considerably smaller than that of the latter (or of the actual diameter of the discharge region), thus defining in effect a "core" region. Each laser beam has a frequency that is exactly resonant with one member of a pair of atomic resonance-line transitions that share a common upper level—i.e., the participating transitions form a Λ-type structure. For a very important reason that will become apparent, there should also be another nearby upper level that is radiatively coupled to both lower Λ levels, i.e., the four levels should form a double-Λ structure. Although several atomic candidates can be considered for the active species in such a system, the use of ^{133}Cs atoms appears to be especially advantageous and, for the sake of definiteness, will be assumed in the model. The optically allowed transitions which connect the four lowest-lying hyperfine levels in Cs (i.e., the levels participating in the D_1 lines) form such a double-Λ structure. A significant fraction of the total discharge-produced fluorescence intensity would be emitted on these transitions.

The axially propagating cw beams Ω and Ω' are assumed to be intense enough so that virtually *all* of the Cs atoms within the cell that lie in the common path of the two beams (i.e., in the "core" region) are coherently phased. This automatically implies that complete transparency would exist throughout the core at exactly ν_o and ν_o', this being the well known condition of electromagnetically induced transparency (EIT). With all linear absorption losses removed at ν_o and ν_o', it would therefore seem only necessary that there exist some independent photonic means for providing gain at these frequencies in order for lasing to occur. The analysis given in the present paper leads to the rather surprising conclusion that in the case of the adopted model only *one* type of photonic mechanism could provide gain at ν_o and ν_o'. This turns out to be a very high order (i.e., four or more photons participating in the unit step) of the nonlinear multiphoton process known as stimulated hyper-Raman scattering (SHRS). In the n-photon SHRS mechanism, incoherent fluorescence light produced by the discharge at the D_1 lines is directly converted by the coherently phased Cs atoms into laser light at the frequencies ν_o and ν_o' (which are also D_1-line frequencies). Despite the high orders of those n-photon SHRS processes that theoretically can result in positive cw optical gain being produced in the model, the estimated total gain does appear to be sufficient to enable cw lasing to occur. This is largely because every optical transition involved in the unit step of such a process is exactly or nearly resonant.

Because of physical uncertainties clouding most of the mechanisms involved in the model, our approach throughout the present paper must necessarily rely upon qualitative reasoning and use of very general physical principles. We suggest that perhaps it is not unreasonable that cautious optimism prevail in the minds of any laser scientists—experimentalists or theoreticians—who might be tempted to explore in real depth some of the concepts and ideas presented here. If the proposed laser idea itself proves to be unfeasible, at least some interesting physics might be revealed. We strongly would like to encourage any such explorations. The authors themselves are currently contemplating initiating an experimental effort to see if the basic laser scheme here proposed can actually be demonstrated in the laboratory.

The present paper is organized as follows. It was noted above that in the model here being employed one starts by assuming that *all* the Cs atoms in the core are coherently phased (i.e., "dressed"). Section II is entirely devoted to a consideration of the various ways by which dressed Λ-type atoms can further be optically excited, the aim here being to see if optical gain can thereby be produced at the bare-atom transition frequencies ν_o and ν_o'. Since one is here only interested in optical excitation of dressed atoms, it makes sense to analyze gain-producing mechanisms with the use of energy level diagrams that are appropriate for dressed atoms. Accordingly, the authors have chosen to utilize throughout Sec. II a Λ-type dressed-atom energy level diagram that is entirely similar to those that first appeared and were explained in Ref. [3], an illuminating paper in which it was shown how such diagrams can be simply utilized to gain insight into both coherent and incoherent optical processes occurring in driven three-level systems. For the benefit of the reader, we summarize some of the main points of Ref. [3] in Sec. II A, emphasizing in particular how simple one-photon transitions (i.e., absorption and fluorescence) occurring with dressed atoms are represented in such diagrams. From such diagrams it immediately becomes apparent why the laser scheme here being explored could only work with an active species possessing a Λ structure—i.e., that use of cascade- or V-type dressed-atom systems in this application can at once be ruled out.

How *multiphoton* transitions occurring between dressed-atom energy levels should be represented is the first topic discussed in Sec. II B. It is proposed that accepted ways of representing one-photon transitions occurring in dressed atoms can be simply modified to apply to the multiphoton case. Although rigorous justification for their use is not provided, the proposed ways of representing *n*-photon transitions in dressed-atom diagrams appear to be natural extensions of the accepted way single photon transitions are represented in such diagrams. Whether or not the former can be justified, they nonetheless form the bases for the main arguments of the present paper. The *n*-photon representation is first applied to stimulated Raman scattering (SRS) processes occurring with dressed atoms. One here notes that the unit step of the SRS process could be represented by any one of four distinct two-photon transition sequences, each of which would result in one laser cavity photon being produced.

In Sec. II B it is next shown that photonic excitation of a Λ atom situated in an otherwise quiescent coherently-phased gas must invariably be accompanied by *a subsequent loss of two laser cavity photons*, irrespective of the type of excitation mechanism involved. From this important conclusion, it directly follows that only very high order excitation processes can provide gain in the proposed cw laser scheme. For example, from the same conclusion it follows that—again, on a cw basis—occurrence of every SRS excitation event would ultimately result in a *net loss* of one laser cavity photon, on the average. Thus pumping via SRS would not be a viable means for producing cw optical gain on the Λ transitions.

In Sec. II C it is explained that one potentially gains access to an effective pumping scheme for the dressed atoms in the proposed laser medium if the bare-atom level diagram for the active atomic species possesses a double-Λ structure. This is postulated to occur in the model. Cs atoms possess such a structure.

Nonlinear excitation of dressed atoms via *nonparametric* (i.e., Raman-type) processes is explored in Sec. II D. Here, it quickly becomes evident that only the class of multi-photon processes known as stimulated hyper-Raman scattering (SHRS) could possibly provide adequate pumping mechanisms for the Cs atoms in the dressed-atom laser model. It is shown that cw gain could conceivably only result from an *n*-photon SHRS process with *n* being $\geqslant 4$ and with pump light being absorbed in each of the first three photonic transitions making up the unit step of the process. In these processes it is presumed that lasing occurs at frequencies ν_o and ν_o' corresponding to one Λ transition pair of a double-Λ structure, with the pump light being discharge-produced fluorescence occurring at the other Λ transition pair.

In Sec. II E estimates are made of the optical gains one could expect to be produced by such high order processes with use of the above pumping scheme. Under the assumption that standard formulae for SHRS gain in randomly-phased atomic media can also legitimately be utilized to estimate optical gain in the dressed-atom case, it is shown that the calculated unsaturated single-pass gain at both ν_o and ν_o' should easily be enough to balance the $\sim 1\%$ net output coupling loss assumed in the model. However, much more restrictive is another requirement that directly follows from the pumping scheme assumed in the model. On the basis of this scheme, it is deduced that the total discharge-produced fluorescence light intensity at the two pump frequencies that would normally be radiated from a column having an area of $1\ \text{cm}^2$ and a length equal to that of the vapor cell, would have to be large enough to sustain an output from the device consisting of two cw laser beams, each with a total power of ~ 18.2 W. (This 18.2 W figure assumes a 1% output coupling. What is rigorously imposed by the model is a value of $1822.5\ \text{W/cm}^2$ for the intracavity-circulating laser power in each of the beams Ω and Ω'.)

In Sec. II F, the highly relevant question of whether or not multiphoton SHRS processes can be driven by purely stochastic light is briefly considered. Results of a theoretical and experimental study reported in 1974 are quoted which show that, at least in the case of broadband SRS (i.e., 2-photon SHRS), pumping with stochastic light can be as effective as pumping with laser light, provided that a number of conditions are satisfied, including having the pump and Stokes waves copropagate in the gain medium with the same group velocities. Since roughly similar conditions would automatically prevail in the dressed-atom model here being considered, some justification perhaps exists for generally postulating (as is done in Sec. II F) that stochastic light could also pump the higher order SHRS processes considered in the present paper.

In Sec. III experimental aspects of the proposed laser device are discussed. A generic type of vessel that enables a long column of hot reactive gas such as Cs vapor to be stably contained while the gas is being excited via an electrical discharge is briefly discussed in Sec. III A.

In Sec. III B, possible experimental configurations with which realization of the device can be attempted are discussed. To be considered satisfactory, any such configuration must include means for injecting intense, externally or internally generated, "starter" laser pulses at both ν_o and ν_o' into the optical cavity of the dressed-atom laser device. The required intracavity-injected energy of the starter pulses would be the energy needed to coherently phase all of the atoms within the core. In the scientific literature dealing with EIT, this amount of energy is usually termed the "preparation loss."

Section IV briefly summarizes the predicted main characteristics of the laser device proposed in the present paper.

II. NONLINEAR PUMPING OF Λ-TYPE DRESSED-ATOM VAPORS

A. Dressed-atom energy level diagram for Λ atoms

Figure 1 represents the dressed-atom energy level diagram for a gas of coherently phased Λ atoms. Diagrams of this

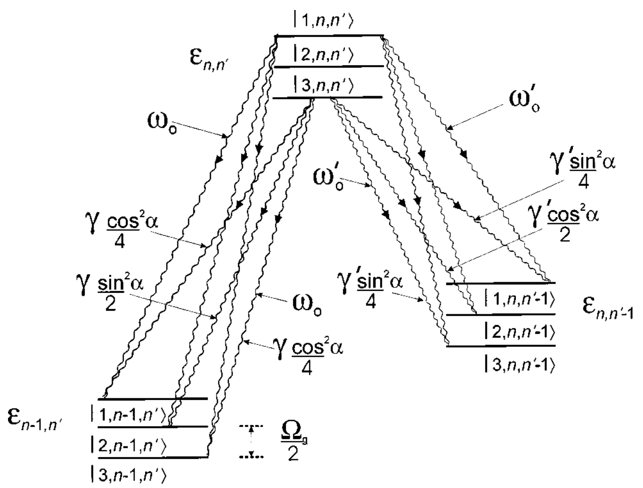

FIG. 1. Diagram showing all spontaneous emission decays which are allowed from the three perturbed states of $\varepsilon_{n,n'}$ to lower multiplicities in Λ-type dressed atoms. Spontaneous emission rates on individual transitions are shown ($\tan\alpha=\Omega'/\Omega$). The quantities γ and γ' are the radiative decay rates for the two bare-atom transitions.

type first appeared and were explained in Ref. [3], an illuminating paper in which it was shown how such diagrams can be simply utilized to gain insight into both coherent and incoherent optical processes occurring in driven three-level systems. Although in Ref. [3] only the cascade-type three-level atomic system is analyzed, extension to the Λ system is trivially simple. To fully comprehend the justification for using diagrams similar to the one shown in Fig. 1 when analyzing dressed-atom photonic events, one must consult Ref. [3]. Here we will largely focus on indicating the ways various transitions occurring in coherently phased Λ atoms are represented in such diagrams.

The perturbed energy levels of a dressed Λ atom form an infinite ladder of multiplicities $\varepsilon_{n,n'}$, each multiplicity containing three nondegenerate levels $|1\rangle$, $|2\rangle$, and $|3\rangle$. Only transitions occurring between adjacent multiplicities are allowed. These are shown as wiggly arrows in Fig. 1. The relative transition probabilities are also indicated in this figure. One can interpret the numbers n,n' associated with each level as the number of photons in two laser cavity modes assumed to be coupled to the Λ gas. The resonant frequencies of these two modes are ω_o and ω_o', i.e., the same as the bare-atom frequencies.

From the allowed transition scheme in Fig. 1, it is apparent why under steady-state conditions all atoms in a coherently phased Λ gas must occupy $|2\rangle$ levels, irrespective of the ratio of Rabi frequencies Ω and Ω'. Establishment of EIT in a steady-state Λ system is represented in this figure by the indication that an upward transition at either ω_o or ω_o' originating from any $|2\rangle$ level is forbidden. One also sees from this figure that coherently phased Λ atoms cannot fluoresce—the $|2\rangle$ levels are indeed "dark state" levels, as is well known. The figure also shows that the dressed-atom absorption spectrum consists of a doublet about each of the bare-atom resonance frequencies ω_o and ω_o'. The two components of each absorption doublet are symmetrically disposed in frequency about the corresponding bare atom frequency, with both doublet splittings being equal to the "generalized Rabi frequency" $\Omega_g=(\Omega^2+\Omega'^2)^{1/2}$. As the intensities of the beams Ω and Ω' are increased, the doublet splittings increase, but the peak absorption strengths and linewidths of all four doublet components remain largely unchanged, provided that the Rabi frequency ratio Ω/Ω' remains the same. Simple analysis contained in Ref. [3] shows that the relative strength ratio of the two absorption doublets is inversely proportional to the square of the ratio of associated Rabi frequencies. All the above properties of coherently phased three-level systems have been well understood for many years, but the rigorous quantum mechanical analyses [4,5] needed to account for these properties at all power levels of the laser beams that dress the atoms can be quite complex and difficult to follow. Dressed-atom diagrams such as Fig. 1 thus offer a lucid, direct way of gaining insight into the properties of any driven three-level system. However, as explained in Ref. [3], such diagrams rigorously apply only in the "secular limit," i.e., when the generalized Rabi frequency Ω_g is much greater than the radiative decay rate of either allowed three-level-atom transition. It will become apparent that, in the operating regime envisioned for the laser device here being considered, this condition is well satisfied.

An immediate conclusion that can be drawn from diagrams such as Fig. 1 is that a cw laser based upon three-level dressed atoms possessing either a cascade-type or V-type energy level structure would be, practically speaking, unrealizable. Unlike coherently phased Λ atoms, coherently phased cascade- or V-type atoms strongly fluoresce. Thus, merely to support a 1-m-long, 1-cm^2-area column of dressed atoms of the latter types would require a continuous application of power in excess of 2 MW. (In this estimate, a dressed-atom density of 10^{15} cm^{-3}, a bare-atom transition wavelength of 10 000 Å, and a bare-atom transition decay time of 10 nsec are assumed.) By contrast, to support a similar column of dressed Λ atoms would ideally require no power, since such atoms do not fluoresce, unless they are additionally excited.

B. Representation of multiphoton transitions in dressed-atom level diagrams

Thus far, it has been noted that a gaseous column of dressed Λ atoms is a remarkably quiescent system, ideally not requiring that any power be extracted from the two spatially overlapping resonant cw beams that propagate through the medium, while simultaneously keeping all the atoms in the paths of the beams coherently phased. However, consider now what would happen if one were to apply *additional* light to the dressed atom system. Specifically, let us suppose that the gaseous column of dressed atoms is irradiated along its axis by intense (incoherent or coherent) light at $\omega_o+(\Omega_g/2)$. The dressed atoms will strongly absorb this light via one of the above mentioned absorption doublet components. Consider what would happen to a dressed atom in, say, the level $|2,n-1,n'\rangle$. Absorption of a photon at $\omega_o+(\Omega_g/2)$ will first move this atom to level $|1,n,n'\rangle$, as represented by one of the upward-pointing arrows in Fig. 2. One next notes that there are four allowed optical transitions (two up and two

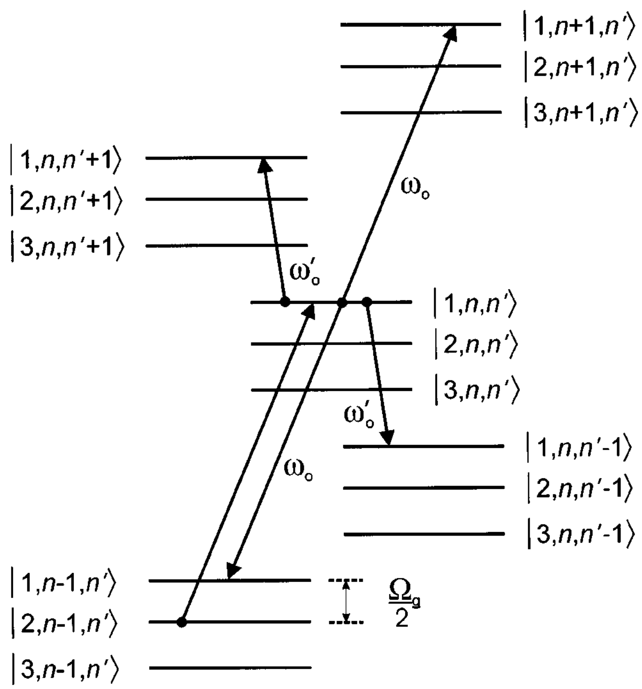

FIG. 2. Representations in a dressed-atom level diagram of all four possible SRS two-photon transition sequences pumped by light applied at the dressed-atom absorption band frequency $\omega_o + (\Omega_g/2)$. Sequences are shown originating from the particular level $|2,n-1,n'\rangle$. In each of the four sequences shown, a single laser photon at ω_o is produced. To produce laser photons at ω_o' via SRS, one would need to apply pumping light at either of the dressed-atom absorption band frequencies $\omega_o' \pm (\Omega_g/2)$.

down) connecting level $|1,n,n'\rangle$ with levels of adjacent multiplicities, with each of the four transitions having the potential to be resonantly driven by one of the cw laser beams. Assume for the moment that the laser-driven transition which takes the excited atom from $|1,n,n'\rangle$ to $|1,n,n'-1\rangle$ occurs. One then sees from the figure that the overall effect of combining absorption of a pump photon at $\omega_o+(\Omega_g/2)$ with stimulated emission of a photon of laser light at ω_o' leads to the production of one laser cavity photon at ω_o. In this case, generation of a single laser cavity photon at ω_o' is represented by the downward-pointing arrow at ω_o' appearing in the figure. However, the numbers of laser cavity photons at ω_o and ω_o' associated with the terminal level $|1,n,n'-1\rangle$ of the combined two-photon transition are, respectively, greater by 1 and less by 1 than the corresponding numbers associated with the level $|2,n-1,n'\rangle$ from which the transition originated. Therefore, the single laser photon produced via this combined two-photon sequence must have the frequency ω_o. One could equally well have selected the second step in the combined process to be, say, the laser-driven transition that takes an atom from $|1,n,n'\rangle$ to $|1,n+1,n'\rangle$. One can see by the same argument just presented that, via this alternative combined process, a single laser cavity photon at ω_o would still be produced. In this process, the second transition in the two-photon sequence is represented by the upward-pointing arrow at ω_o shown in the figure, with this arrow now representing *loss* of a laser cavity photon at that frequency. However, the process being considered terminates on dressed-atom level $|1,n+1,n'\rangle$, and the number of photons in the laser cavity mode at ω_o associated with this level exceeds by two the corresponding number associated with $|2,n-1,n'\rangle$, the dressed-atom level from which the process originated. Hence, one deduces that a net production of one laser cavity photon at ω_o would again result from the alternative combined process. The same statement holds for the other two combined processes shown in Fig. 2. For laser photons at ω_o' to be created via SRS, pump light would have to be applied at $\omega_o' \pm (\Omega_g/2)$.

In subsequent sections it will be investigated if high order *n*-photon SHRS transitions occurring in dressed atoms can increase the number of laser cavity photons. It will then be assumed that one should follow essentially the same laser photon counting procedure just described—i.e., one should combine the number of laser photons that are apparently gained (or lost) in a given sequence of upward and downward pointing arrows representing a multiphoton transition with the number one infers to have been gained (or lost) when the n,n' quantum numbers associated with the level upon which the multiphoton transition terminates are compared with those associated with the level from which the multiphoton transition originates.

From the preceding, one might gather that SRS should be a viable gain-producing mechanism for the cw dressed-atom laser in the model, since occurrence of an SRS excitation event was shown to produce one laser photon. However, a very important loss mechanism has thus far been overlooked. From Fig. 1, one sees that a Cs atom excited to a $|1\rangle$ or $|3\rangle$ SRS terminal level will decay by spontaneous emission via the transitions indicated in the figure. Consider the various decay sequences that would be possible for an atom excited by SRS if the terminal level were, say, the level $|1,n,n'\rangle$. For simplicity, assume that $\tan\alpha=1$ and that $\gamma=\gamma'$. (No loss of generality is involved in making these assumptions.) The excited atom then could decay (with *total* probability $\frac{1}{2}$) to either level $|2,n-1,n'\rangle$ or $|2,n,n'-1\rangle$. Only one laser cavity mode photon would be lost in this way, since subsequent decays would be forbidden. However, the originally excited atom in $|1,n,n'\rangle$ could also decay via a *two-step* process—first to a $|1\rangle$ or $|3\rangle$ level, then to a $|2\rangle$ level. The total probability for this to occur would be $\frac{1}{4}$. Likewise, the originally excited atom could spontaneously decay in a three-step process with a total probability of $1/8$, or in a four-step process with total probability of $1/16$, etc. One can easily see that the most probable number of *laser* photons that would be lost by an atom in the $|1,n,n'\rangle$ level undergoing spontaneous emission decay would be *two*. The photons spontaneously emitted in the decay sequences would be radiated in all directions. From Fig. 1, one sees that their frequencies would be distributed among five closely spaced bands centered about ω_o and five closely spaced bands centered about ω_o'. The same result would hold for a dressed atom excited to *any* $|1\rangle$ or $|3\rangle$ level via *any* type of photonic process, whether it be linear or nonlinear.

Considering that one photon was added to a laser cavity mode via the SRS excitation event itself, one therefore concludes that the *net* effect (i.e., on a cw basis) of such an event is a *loss of one laser photon*. Thus, pumping via the two-

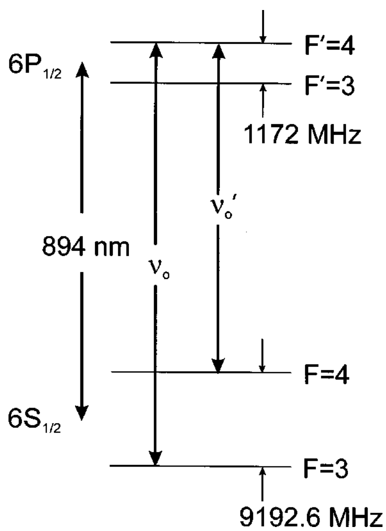

FIG. 3. Lowest energy double-Λ structure in Cs. In this figure, lasing is depicted as occurring on the lower Λ pair of transitions.

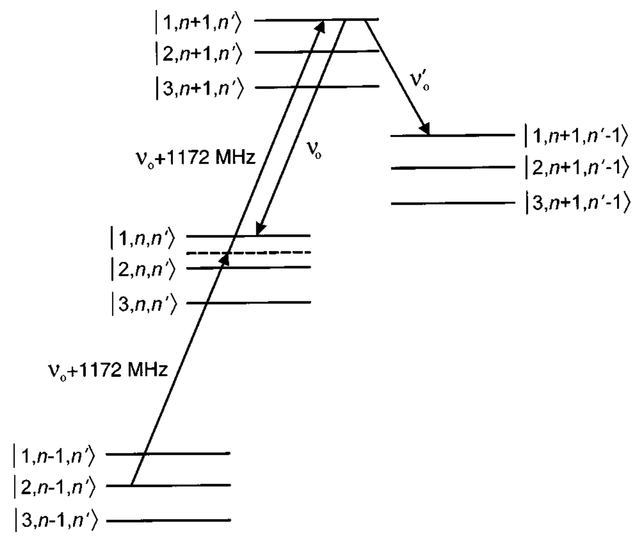

FIG. 4. Two resonantly-enhanced 3-photon SHRS unit step sequences are shown, both of which result in the production of two laser photons at ν_o. In this figure, a value of the generalized Rabi frequency Ω_g is assumed which allows the pump light component at ν_o+1172 MHz to be two-photon resonant with the transitions shown.

photon excitation process of SRS cannot by itself result in cw optical gain being produced on the Λ transitions in the model. It thus becomes necessary to consider higher-order multiphoton pumping processes, if one expects to find mechanisms which can provide optical gain for a gas of Λ-type dressed atoms. This will be discussed in detail in Sec. II D.

C. Source of incoherent light for pumping the dressed Cs atoms in the model

Figure 3 shows the lowest-lying energy levels for the Cs atom. It is seen that the levels form a double-Λ system. All four optical transitions connecting the two hyperfine levels of the $6P_{1/2}$ state with those of the $6S_{1/2}$ state are dipole allowed.

In attempting to identify in Sec. II D nonlinear laser pumping mechanisms that could be effective in the model, we will initially assume the two lasing transitions to be those shown in the diagram of Fig. 3, i.e., the two transitions making up the lower Λ structure. It will then be investigated whether there is enough discharge-produced fluorescence intensity at the two nonlasing transitions of Fig. 3, i.e., those making up the upper Λ structure, to induce lasing in the model.

In principle, the situation could be just the reverse from the one shown in Fig. 3, i.e., the two upper Λ transitions could be the lasing transitions, while pump light would be provided at the two lower Λ transitions. There is also the remote possibility that these two alternative pumping-lasing schemes could function *simultaneously*, with lasing occurring at all four double-Λ frequencies, and with the pump light being the discharge-produced fluorescence generated on the same four transitions. However, since there appear to be some serious conceptual difficulties associated with this last mentioned regime, and since at present there does not seem to be any critical need that it prevail in the model, it will, for the sake of simplicity, be ignored throughout the remainder of the present paper.

D. Photonic excitation of dressed Λ atoms via *n*-photon stimulated hyper-Raman scattering (SHRS)

In view of the analysis given in Sec. II B it is evident that one must consider pumping the Λ-type dressed-atom vapor of the proposed laser device via a nonlinear photonic mechanism of order higher than 2, the value that characterized SRS. In the present section the authors outline the only type of nonlinear photonic process they believe could possibly result in cw optical gain being produced when dressed Cs atoms in the model are excited by such a process. This is *n*-photon stimulated hyper-Raman scattering (SHRS), a *nonparametric* process involving dressed atoms being driven from initially occupied $|2\rangle$ levels to unoccupied terminal $|1\rangle$ or $|3\rangle$ levels. (SRS is equivalent to 2-photon SHRS.) Multiphoton processes which in the unit step return the atom to the initial state are termed *parametric* processes, but such processes cannot be driven by incoherent pump light and will be ignored in the present paper.

In Fig. 4, two transition sequences, both representing a specific 3-photon SHRS scheme for exciting Cs dressed atoms in the proposed device, are shown. In this scheme, it is assumed that the frequencies of the two cw laser beams that dress the atoms occur on the Cs-atom transitions marked ν_o and ν_o' in Fig. 3, and that incoherent pump light is provided by discharge-produced fluorescence occurring on the upper Λ pair of $6P_{1/2} \leftrightarrow 6S_{1/2}$ transitions. In Fig. 4, it is also assumed that the cw laser beams irradiating the atoms have a generalized Rabi frequency such that the pump light component at ν_o+1172 MHz is two-photon resonant with the transitions shown. (The pump light component at ν_o' +1172 MHz will then automatically be capable of resonantly driving the two-photon pumping transition that would excite an atom from, say, level $|2,n-1,n'\rangle$ to level $|1,n-1,n'+2\rangle$. Additionally, resonantly enhanced two-photon pumping

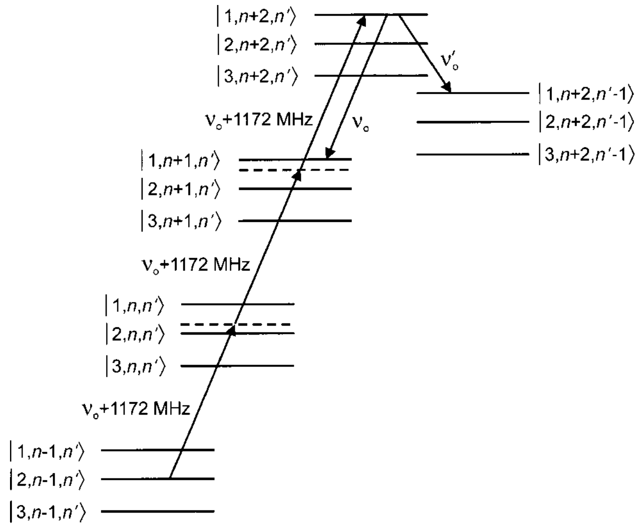

FIG. 5. Two resonantly-enhanced 4-photon SHRS unit step sequences are shown, both of which result in the production of three laser photons at ν_o. A value of the generalized Rabi frequency Ω_g is assumed which allows the pump light component at ν_o+1172 MHz to be three-photon resonant with the transitions shown.

would occur via processes in which single photons at each of the pump frequencies ν_o+1172 MHz and $\nu_o'+1172$ MHz are simultaneously absorbed.)

One notes that, in the unit steps of both three-photon processes shown in Fig. 4, a dressed Cs atom is excited from an occupied $|2\rangle$ level to an unoccupied $|1\rangle$ level, and *two* laser photons at ν_o are produced. (Only when the SHRS excitation process involves absorption of pump light at $\nu_o'+1172$ MHz, will laser photons at ν_o' be produced.) However, from the main result of Sec. II B, one again must here infer that a simultaneous 3-photon SHRS excitation event taking an atom from level $|2,n-1,n'\rangle$ to either level $|1,n,n'\rangle$ or level $|1,n+1,n'-1\rangle$ would inevitably be followed by a delayed loss of two laser photons. Thus, on a cw basis, the three-photon SHRS dressed-atom excitation process shown in Fig. 4—whenever it occurs—would provide neither optical gain nor optical loss for either of the two cw laser beams that propagate through the gas and dress the Cs atoms. In the end, what effectively happens each time the multiphoton event of Fig. 4 occurs is that two fluorescence pump photons at ν_o+1172 MHz are (wastefully) converted into two incoherent light photons, the latter being radiated in all directions at frequencies corresponding to two of the ten discrete bands mentioned in Sec. II A.

Upon a little reflection, one realizes that *optical gain in the model could only result from processes in which three or more pump photons are initially absorbed in the sequence of transitions representing the unit step of the process*. Each of the two equally resonant sequences diagrammed in Fig. 5 constitutes an example of the lowest order SHRS process that could create three laser photons at ν_o in the unit step. Since subsequent loss of two laser photons would again invariably occur each time a dressed atom is excited via either of these sequences, one sees that, on a cw basis, an overall gain of one laser photon would be achieved. In principle, therefore, either 4-photon SHRS sequence in Fig. 5 can be considered a potential laser pumping mechanism for the model. One can conceptually construct SHRS excitation processes that would also provide a net gain of one photon by increasing the number of downward-pointing arrows in Fig. 5. However, these processes would be of higher order than the 4-photon SHRS process of Fig. 5. Consequently, one would normally expect them to have much lower transition probabilities. In Sec. II E it will be seen that this is not necessarily the case.

In Fig. 5, it has been assumed that the pumping part of the unit step of the multi-photon process constitutes a resonant three-photon transition in which three discharge-produced fluorescence photons at ν_o+1172 MHz are absorbed. By postulating pumping to occur via a resonant three-photon transition, rather than via a resonant two-photon transition, one thus avoids the possibility that the wasteful process of Fig. 4 could occur. However, by assuming the three-photon-resonant condition, one constrains the generalized Rabi frequency in the model to be $\Omega_g/2=2\pi\times3\times1172$ MHz, i.e., $\Omega_g\approx4.4\times10^{10}$ sec^{-1}. Assuming equal Rabi frequencies ($\Omega=\Omega'$), one has $\Omega\approx3.1\times10^{10}$ sec^{-1}. The Cs $6S_{1/2}\leftrightarrow6P_{1/2}$ transition dipole moment (in SI units, which will be used throughout Sec. II E) is taken to be $\mu_o=2.8\times10^{-29}$ Cm, the value given in [6]. Since $\mu_oE=\hbar\Omega$, where E is the peak amplitude of the Ω laser field, one has $E\approx117\,159$ V m^{-1}. This corresponds to a cycle-averaged, intracavity circulating Ω laser beam power $I_S\approx18.2\times10^6$ W m^{-2} (1822.5 W cm^{-2}), since $I_S=(1/2)\varepsilon_oc|E|^2$. The Ω' laser beam would have equal intensity. It is thus seen that, for a Cs dressed-atom laser to work with the scheme shown in Fig. 5, the laser would necessarily have to operate at an uncomfortably high cw power level. Assuming the total power coupled out from the laser cavity to be one percent of the intracavity power, one would thus be required to utilize a discharge tube long enough and powerful enough so that the total fluorescence power radiated over the length of the discharge in the two hyperfine lines at ν_o+1172 MHz and at $\nu_o'+1172$ MHz could support generation of two $\sim$18.2 W/cm^2 laser beams.

E. Optical gain for *n*-photon SHRS excitation of dressed atoms

As noted above, each of the two sequences shown in Fig. 5 represents the unit step of a theoretically possible four-photon SHRS process by which three discharge-produced fluorescence photons at ν_o+1172 MHz can be converted into three photons of laser light at ν_o in a Cs dressed-atom vapor. Equally resonant such processes resulting from discharge-produced fluorescence photons at $\nu_o'+1172$ MHz being absorbed in any or all of the three pumping steps would also obviously provide optical gain at the two laser frequencies, and these contributions to the latter must eventually be included. However, we begin the present section by estimating the optical gain that in principle should be attainable with either one of the two SHRS sequences shown in Fig. 5.

Using standard methods of nonlinear optics, one can evaluate optical gains characterizing *n*-photon SHRS processes occurring in gases of *randomly*-phased (i.e., *non*-coherently-phased) atoms. Here we shall assume that formu-

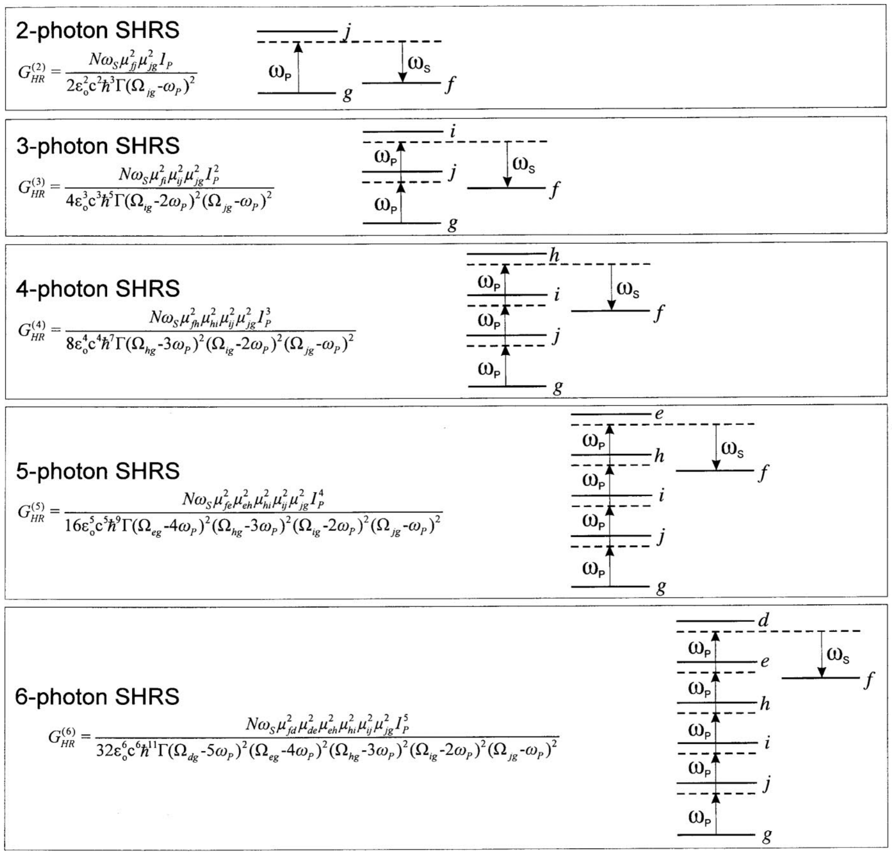

FIG. 6. Standard formulas for n-photon SHRS optical gain that are applicable to randomly phased atomic gases. Level diagrams in which the corresponding unit step sequences are depicted are also shown.

las for n-photon SHRS optical gain derived for randomly phased atoms would also apply in the dressed-atom case, provided that there exists an obvious correspondence between the sequences of photonic transitions in the unit steps of the two processes being compared.

In Fig. 6 standard expressions (cf. [7]) for n-photon SHRS gain in randomly-phased atomic gases are listed for the cases $n=2-6$. In addition, the corresponding schematic energy level diagram is shown for each process. While these formulas all are written for the case of a single pump frequency ω_P, it will here be assumed that they also all apply when some of the pump frequencies are different, since the important factors here are the transition dipole moments, the resonance denominators, and the pump light intensities. The hyper-Raman gain $G_{HR}^{(n)}$ given by these formulas represents an exponential intensity gain per unit length, that is, in the absence of pump power depletion and/or saturation in the efficiency of the SHRS process, the intensity of the laser Stokes-wave beam at ω_S would increase by a factor $e^{G_{HR}^{(n)} l}$ in traveling a distance l.

Before applying the expression for 4-photon SHRS gain appearing in Fig. 6 to one of the two dressed-atom excitation schemes shown in Fig. 5, one should take note of a striking feature that here arises because dressed atoms are involved. Standard expressions for SHRS gain always imply summations over all excited energy levels, and the same should hold when the former are applied to dressed-atom systems. From Fig. 5, one might initially suspect that, due to quantum interference, the transition probability for the four-photon process depicted might be somewhat reduced by virtue of the fact that the effective intermediate state for the first transition shown could be either a $|1\rangle$ or a $|3\rangle$ level, with the former lying above, and the latter lying below, the virtual intermediate state for the same transition. If the dipole moments $\mu_{2\rightarrow 1}$ and $\mu_{2\rightarrow 3}$ had the same sign, this would lead to a partial cancellation of the overall four-step transition probability. However, from Ref. [3] one sees that $\mu_{2\rightarrow 1} = -\mu_o \sin\alpha/\sqrt{2}, \mu_{2\rightarrow 3} = \mu_o \sin\alpha/\sqrt{2}$ ($\tan\alpha = \Omega/\Omega'$), so that the transition probability contributions arising from the $|1\rangle$ and $|3\rangle$ intermediate state levels do not cancel one another, but in fact additively combine. The same remark would also hold in the case of the second transition. Here, either the $|1\rangle$ or $|3\rangle$ levels of the next highest multiplicity could again serve as intermediate states. The corresponding transition probability contributions would again additively combine, since $\mu_{1\rightarrow 1} = \mu_o \cos\alpha/2, \mu_{1\rightarrow 3} = -\mu_o \cos\alpha/2$. In brief, no transition probability cancellation due to quantum interference arises when n-photon SHRS excitation is applied to a dressed-atom gas. This example illustrates one of the many important advantages gained in utilizing nonlinear excitation of dressed-atom vapors to generate laser beams at different frequencies. That such advantages automatically accrue with use of this generation technique was first theoretically predicted in Ref. [8]. As illustrated by the example discussed in the Introduction, many subsequent experimental studies have demonstrated that high efficiencies of laser beam generation can indeed be attained when this general scheme is employed. However, in evaluating $G_{HR}^{(4)}$ for the transition scheme of Fig. 5, we will assume that only intermediate state levels labeled $|1\rangle$ in Fig. 5 contribute to the transition probability; that is, contributions stemming from the somewhat less resonant $|3\rangle$ levels will, for the sake of simplicity, here be ignored.

Assignment of frequency factors appearing in the denominator of the expression for $G_{HR}^{(4)}$ for the transitions shown in Fig. 5 is straightforward. For the first pumping step, the offset is $(\Omega_{jg}-\omega_P)=2\pi\times 2\times(1172\text{ MHz})=1.47\times 10^{10}\text{ sec}^{-1}$. For the second, it is $(\Omega_{ig}-2\omega_P)=2\pi\times(1172\text{ MHz})=7.36\times 10^{9}\text{ sec}^{-1}$. There is an exact resonance at the third pumping step, so that in the usual manner one must here utilize a damping factor to avoid the presence of an infinite singularity. We take this damping factor to be the Cs Doppler width $\Delta\omega_D$ (expressed as an angular frequency). For the approximate temperatures ($T\approx 500$ K) at which it is envisioned that the Cs dressed-atom laser would operate, $\Delta\nu_D\approx 500$ MHz. Therefore, one here has $(\Omega_{hg}-3\omega_P)=\Delta\omega_D\approx 3.14\times 10^{9}\text{ sec}^{-1}$. We will also assume $\Delta\omega_D$ to be the value of the Raman linewidth Γ appearing in the denominators of Fig. 6.

The quantity I_P appearing in the expression for $G_{HR}^{(4)}$ in Fig. 6 would here be the intensity of isotropically radiated fluorescence pump light at ν_o+1172 MHz present everywhere in the region of the vapor cell where the laser beams propagate. We here take this quantity to be 0.1 W cm^{-2} (1000 W m^{-2}). (For simplicity, the same value will also be assumed for the intensity of the fluorescence pump light at $\nu_o'+1172$ MHz.) Let it be assumed that the Cs atomic density in the vapor cell is 10^{21} m^{-3}. For the excitation scheme of Fig. 5, the dipole transition moments appearing in the formula for $G_{HR}^{(4)}$ would be $\mu_{fh}=\mu_{hi}=\mu_{ij}=\mu_{1\rightarrow 1}$ and $\mu_{jg}=\mu_{2\rightarrow 1}$. Assuming laser operation with $\Omega=\Omega'$ implies that the absolute values of $\mu_{2\rightarrow 1}$ and $\mu_{1\rightarrow 1}$ would be $\mu_o/2$ and $\mu_o/(2\sqrt{2})$, respectively. The value of μ_o was noted earlier. The angular frequency ω_S ($\equiv\omega_o$) is here $2.2\times 10^{15}\text{ sec}^{-1}$. Upon substitution of the various above parameter values, one finds the power gain coefficient for either of the 4-photon SHRS sequences in Fig. 5 to be only $G_{HR}^{(4)}\approx 2.13\times 10^{-8}\text{ m}^{-1}$. One immediately realizes that this gain coefficient should be multiplied by a factor 16 for the following reasons. As already noted, there are 8 possibilities for realizing an equally strong three-photon-resonant pumping sequence with use of photons at either ν_o+1172 MHz or $\nu_o'+1172$ MHz. For any of these 3-photon pumping sequences, there would be four ways of representing the fourth transition in the overall SHRS sequence—i.e., the laser-frequency arrow could be either at ν_o or ν_o', and could point either upwards (cf. Fig. 2) or downwards (cf. Figs. 2 and 5). Since this estimate of how much $G_{HR}^{(4)}$ should be increased combines the gain at both laser frequencies, one must divide it by 2, resulting in a value of $G_{HR}^{(4)}\approx 3.4\times 10^{-7}\text{ m}^{-1}$—still, however, an exceedingly small value.

However, before concluding that the fluorescence pump light intensities assumed above are woefully inadequate for lasing to occur in the model, let us first seek to determine if significant additional optical gain could in theory result from SHRS processes that are of order $n>4$, but in which three fluorescence pump light photons are still absorbed in the unit step of the process. The motivation for doing this is based upon the fact that the expression for $G_{HR}^{(n)}$ would now contain the factor $I_S^{(n-4)}$. As explained earlier, in the present model I_S is constrained to have the large value $I_S=18.2\times 10^{6}\text{ W m}^{-2}$ (1822.5 W cm^{-2}). It is thus possible that, due to the presence of the factor $I_S^{(n-4)}$, $G_{HR}^{(n)}$ $(n>4)$ might actually have a greater value than $G_{HR}^{(4)}$, despite the higher order of the former process.

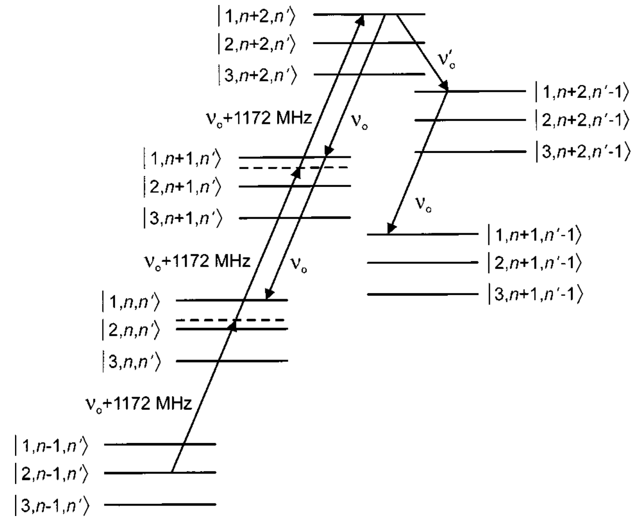

FIG. 7. Two resonantly-enhanced 5-photon SHRS unit step sequences are shown, both of which result in the production of three laser photons at ν_o. The generalized Rabi frequency Ω_g has the same value as in Fig. 5.

Consider for the moment the two 5-photon SHRS dressed-atom excitation processes shown in Fig. 7, which are seen to be basically the same as the 4-photon processes of Fig. 5, except that there are now *two* downward-pointing laser-frequency arrows. (The net cw photon gain in Fig. 7 is, however, still the same as in Fig. 5—i.e., one laser photon.) From Figs. 5–7 it follows that the ratio of SHRS gains for adjacent order processes in the Cs dressed-atom-laser model is evidently always $G_{HR}^{n+1}/G_{HR}^{n}=4\mu_{1\rightarrow 1}^2 I_S/2\varepsilon_o c\hbar^2(3.14\times 10^9)^2\approx 4\times 3.15=12.6$. Therefore, one has $G_{HR}^{(5)}\approx 4.3\times 10^{-6}\text{ m}^{-1}$, which is still too small a gain value to be useful. However, one can next simply consider the optical gain values that would result from still higher-order SHRS processes, since it was just shown that $G_{HR}^{(n)}=(12.6)^{n-4}G_{HR}^{(4)}$. In this way, one finds, for example, that $G_{HR}^{(9)}\approx 0.11\text{ m}^{-1}$, which is more than ten times the value needed for cw lasing to occur in the model when roughly one percent of the intracavity circulating laser power is coupled out. It would appear, therefore, that having sufficient *unsaturated* optical gain should not be a problem with the dressed-atom-laser model.

F. Pumping of SHRS with broadband stochastic light

A serious question regarding the proposed n-photon SHRS excitation mechanism relates to the assumption tacitly made in all of the foregoing that this photonic process could be driven by incoherent fluorescence pump light. At present, the best the authors can do in trying to confront this question is to note that there is compelling evidence in the scientific literature that pumping of SRS (i.e., *two*-photon SHRS) can, under certain conditions, be done as effectively with broadband incoherent light as with narrow-band laser light. For example, the results of a theoretical and experimental investigation of SRS in the field of a Gaussian noise pump in a medium with active length l are presented in Ref. [9], where it is shown that the nature of the stimulated scattering depends upon the relationship of the correlation time τ_{cor} of the noise-pump field, on the one hand, and the transverse relaxation time T_2, and the characteristic group-lag time T_3, on the other hand. For copropagating pump and Stokes waves, $T_3 = l(1/u_P - 1/u_S)$, where u_P and u_S are the respective group velocities. For opposing waves, $T_3 = l(1/u_P + 1/u_S) \approx 2l/c$. In atomic gases, SRS typically occurs in the forward direction when the regime $T_2 > \tau_{cor} > T_3$ is satisfied. It is shown theoretically in [9] that, for this regime, a broadband noise pump is as effective as a coherent monochromatic pump having the same intensity. It would seem that the same result might also apply when dressed atoms are excited via n-photon SHRS in the proposed laser device, the reason being that the same inequality $T_2 > \tau_{cor} > T_3$ is likely to prevail. The requirement that pump and Stokes waves be copropagating is basically satisfied if the former is considered to be the discharge-produced fluorescence photon flux directed along the axis of the gas-containing vessel. In the proposed device, the quantity T_3 would be almost identically zero, since all pump and Stokes-wave frequencies occur within the two narrow spectral regions in which EIT is established, i.e., the spectral intervals $|\omega - \omega_o| \leqslant (\Omega_g - \Delta\omega_D)/2$ and $|\omega - \omega_o'| \leqslant (\Omega_g - \Delta\omega_D)/2$. As can be seen from plots of χ', the real part of the dressed-atom linear susceptibility (cf. Fig. 2 of [8], or Fig. 13 of [10]), the slope of this function changes very little in the above spectral intervals, implying constant group velocities over the same intervals.

In the theory presented in Ref. [9], it is deduced that, in the regime $T_2 > \tau_{cor} > T_3$, the linewidth of the SRS Stokes wave generated is approximately that of the stochastic pump light. This would imply that the spectral width of laser beams generated in the proposed Cs discharge-pumped, dressed-atom laser device should always be approximately 500 MHz.

III. EXPERIMENTAL APPROACHES FOR TESTING FEASIBILITY OF THE PROPOSED LASER DEVICE

A. Containment vessel for the atomic vapor and electrical discharge

To maintain a stable, arbitrarily long, isothermal column of pure Cs vapor, at pressures adjustable anywhere over a wide range ($\sim$0.01–100 Torr), and to provide a means for producing throughout most of this column intense $6S_{1/2}$-$6P_{1/2}$ fluorescence via electronic impact excitation, one can effectively utilize what is termed a *heat-pipe discharge tube (HPDT)*. Such robust devices were first proposed [11] and experimentally demonstrated [12] more than thirty years ago. A schematic diagram of an HPDT is shown in Fig. 8. The principles by which such a device operates when the continuous electrical discharge occurs axially are discussed in [12].

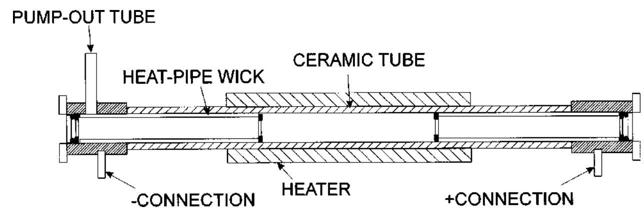

FIG. 8. Schematic diagram of a heat-pipe discharge tube (HPDT) with an axially occurring discharge.

In the optical gain estimates made in Sec. II D, a Cs atom density of 10^{21} m^{-3} was assumed. This is seen to correspond roughly to the low end of the pressure range over which an HPDT can effectively operate. Use of higher Cs pressures would result in greater optical gain, but would also require that proportionally higher laser pulse energies be used to "start" the Cs dressed-atom laser (Sec. III B). Our present view is that experimental realization of the Cs laser device would be easiest to attempt at the lower pressures.

B. Cavity configurations for "starting" discharge-pumped dressed-atom lasers

Thus far in the present paper, it has been assumed that a preexisting column of Cs dressed atoms is nonlinearly driven by fluorescence pump light, resulting in the continual generation of enough additional laser photons to replace those which leave the laser cavity in the form of the cw laser output beams produced by the device. It was explained in Sec. II A that, once coherently phased, a gas of Λ-type atoms essentially does not require additional power to be expended in order for it to remain in this prepared state. However, to initially form, for example, a 1-m-long column of coherently phased Cs atoms at a density of 10^{15} cm^{-3} would require a total "preparation energy" [13] of roughly 20 mJ cm^{-2}. This energy would have to be supplied to the Cs vapor cell in the device through direct irradiation of the latter by simultaneous pulsed laser beams at ω_o and ω_o', with the energy of each beam being at least 10 mJ cm^{-2}. Since this value represents an intracavity-injected energy, a somewhat challenging technical problem presents itself here, in view of the conclusion made in Sec. II E that the total transmittance of both cavity mirrors should not exceed $\sim$1%. A rather extensive amount of equipment would apparently be needed to "start" a Cs discharge-pumped laser in this manner. This equipment is diagrammed in Fig. 9. In initial attempts to demonstrate operation of the device, it might be best to work with small area beams, e.g., $\sim$0.1 cm^2. The total starting pulse energy applied to the 1% transmitting mirror in Fig. 9 would then have to be $\sim$200 mJ. Although the frequencies of the two starting laser beams should be accurately centered at ω_o and ω_o', no purpose would be served in making the line widths of these beams less than about 500 MHz. Although there would exist

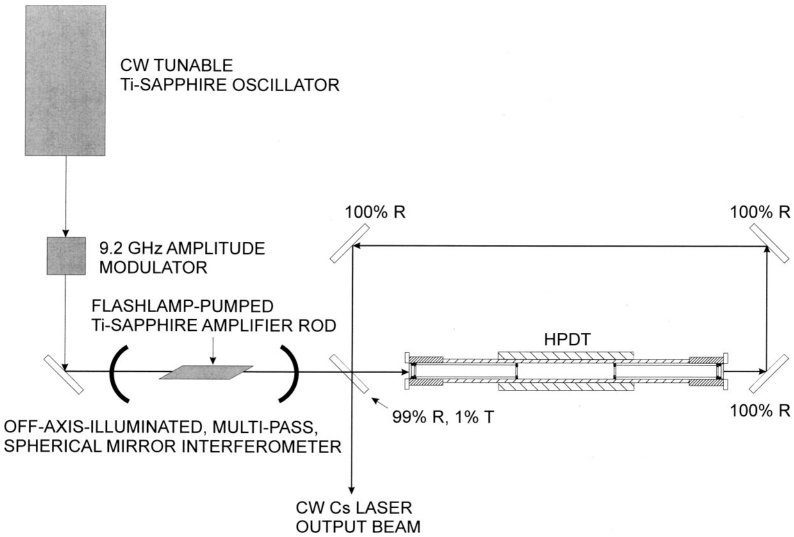

FIG. 9. Diagram of apparatus that can be used to initiate cw operation of a Cs discharge-pumped dressed-atom laser.

some latitude in the choice of starting laser pulse widths, a measure of guidance is provided by considerations such as those that were presented in Sec. II D. For example, it would probably be best for the circulating intracavity power of each of the pulsed starting laser beams to exceed the 1.8 kW/cm^2 cw steady-state value expected in the case of a Cs dressed-atom laser. In a 0.1 cm^2 beam, therefore, each intracavity starting laser beam power should be no less than ~200 W. This would imply a starting laser pulse width ~5 μ sec. After making a final pass through the Ti:sapphire amplifier rod in Fig. 9, each starting laser beam should therefore have a power ~20 kW. This power level should be achievable by multipassing the modulated cw Ti:sapphire laser beam six or seven times through the Ti:sapphire amplifier rod, assuming that the latter is pumped by a relatively fast (~10 μ sec) flashlamp. In this way, in principle, Cs cw dressed-atom laser action could be started on either of the Cs double-Λ transition pairs.

If starting the proposed dressed-atom laser were to always require the use of equipment as complex as that shown in Fig. 9, the laser, even if it were realizable, would clearly represent a rather impractical device. The authors believe that the proposed laser could perhaps be started in a much simpler way, using a configuration similar to the one sketched in Fig. 10. Here the Ti:sapphire rod is simply incorporated into the Cs-laser cavity as an extra element. No basis for tuning is provided, in order to avoid any significant additional optical cavity loss. When the rod is pumped by an external light pulse, very strong Ti:sapphire laser action will occur over a very wide band of frequencies that would normally include all four Cs $6S_{1/2}$-$6P_{1/2}$ optical transitions. In a gas of randomly phased atoms, these transitions would of course all be strongly absorbing, and this would initially prevent the pulsed Ti:sapphire lasing from occurring exactly at the resonance frequencies. However, strong Ti:sapphire lasing would occur in spectral regions that closely abut the Cs resonances. Via various n-photon SHRS processes driven by the intense Ti:sapphire laser light, nonlinear excitation of the Cs atoms conceivably could then happen, leading to the eventual establishment of discharge-pumped, cw dressed-atom laser action on two of the four Cs $6S_{1/2} \leftrightarrow 6P_{1/2}$ transitions as the Ti:sapphire laser pulse energy circulating in the cavity slowly decays. A potential advantage of this scheme is that it would be relatively simple and inexpensive to try.

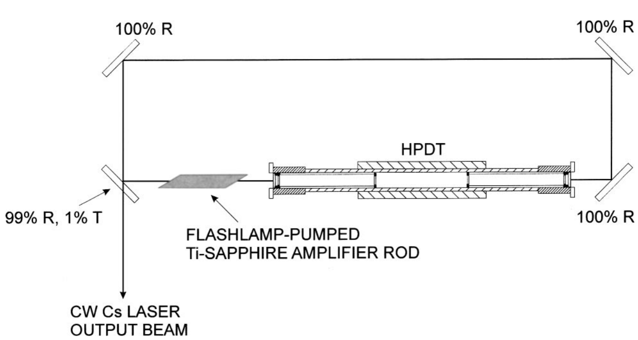

FIG. 10. A possible alternative configuration for initiating cw operation of a Cs discharge-pumped dressed-atom laser.

IV. SUMMARY

In the present paper, the feasibility of constructing a discharge-pumped, cw dressed-atom gas laser has been examined. It is concluded that there is some chance such a device could be made to operate when a (1-to-2)-meter-long column of coherently phased Cs atoms becomes additionally excited by sufficiently-high-order stimulated hyper-Raman scattering (SHRS) processes. Via such processes, discharge-produced fluorescence at two Cs $6S_{1/2}$-$6P_{1/2}$ hyperfine transitions forming a Λ pair can theoretically become converted to cw laser radiation at the frequencies of the other $6S_{1/2} \leftrightarrow 6P_{1/2}$ Λ pair. The adopted pumping scheme constrains the value of the intracavity circulating cw beam power at each of the two lasing frequencies to be ~1.8 kW/cm^2. While estimates of the single-pass unsaturated optical gain in the model indicate that it could be as high as, say, 1%, one would nonetheless have to ascertain that the $6S_{1/2} \leftrightarrow 6P_{1/2}$ fluorescence power integrated along the length of the discharge would be large enough to support the equivalent single-pass power gain (i.e., 18 W/cm^2 per laser beam). To initiate cw lasing of the device on either Λ-transition pair would typically require simultaneous injection into the laser cavity of two $\sim$5-μsec-long resonantly tuned laser pulses, each with an intracavity energy of at least 10 mJ/cm^2.

ACKNOWLEDGMENTS

P.P.S. is grateful to IBM Research management for having allowed him the post-retirement use of office and library facilities for the past three-and-a-half years. J.H.G. acknowledges partial support for this work through the Los Alamos National Lab LDRD-ER program.

[1] S. Alam, *Lasers without Inversion and Electromagnetically Induced Transparency* (SPIE Press, Bellingham, WA, 1999); M. O. Scully and M. S. Zubairy, *Quantum Optics* (Cambridge University Press, Cambridge, England, 1997); S. E. Harris, Phys. Today **50**(7), 36 (1997); E. Arimondo, in *Progress in Optics*, edited by E. Wolf (North-Holland, Amsterdam, 1995), Vol. 35, p. 257.
[2] A. J. Merriam, S. J. Sharpe, M. Shverdin, D. Manuszak, G. Y. Yin, and S. E. Harris, Phys. Rev. Lett. **84**, 5308 (2000).
[3] C. Cohen-Tannoudji and S. Reynaud, J. Phys. B **10**, 2311 (1977).
[4] A. S. Manka, H. M. Doss, L. M. Narducci, P. Ru, and G.-L. Oppo, Phys. Rev. A **43**, 3748 (1991).
[5] L. M. Narducci, M. O. Scully, G.-L. Oppo, P. Ru, and J. R. Tredicce, Phys. Rev. A **42**, 1630 (1990).
[6] R. B. Miles and S. E. Harris, IEEE J. Quantum Electron. **QE-9**, 470 (1973).
[7] D. C. Hanna, M. A. Yuratich, and D. Cotter, *Nonlinear Optics of Free Atoms and Molecules* (Springer-Verlag, Berlin, 1979).
[8] S. E. Harris, J. E. Field, and A. Imamoğlu, Phys. Rev. Lett. **64**, 1107 (1990).
[9] S. A. Akhmanov, Yu. E. D'yakov and L. I. Pavlov, Sov. Phys. JETP **39**, 249 (1974).
[10] M. O. Scully, Phys. Rep. **219**, 191 (1992).
[11] R. T. Hodgson, U.S. Patent No. 3654567 (4 April 1972).
[12] P. P. Sorokin and J. R. Lankard, J. Chem. Phys. **55**, 3810 (1971).
[13] S. E. Harris and Z.-F. Luo, Phys. Rev. A **52**, R928 (1995).