"The QASER: Recent Progress"

by Marlan O. Scully

(with W. Lamb, M. Lukin, W. Schleich, and A. Svidzinsky)

Abstract
Lasers and masers typically require population inversion. But with phase coherent atoms (phasers), we get lasing without inversion (e.g., 10% of the atoms excited). Now we find that it is possible to get coherent light emitted with no atoms excited, via Quantum Amplification of Superradiant Emission of Radiation (QASER).
OUTLINE

1. Laser Concepts

2. Quantum Noise Quenching and Lasing Without Inversion via Phase Coherence

3. QASER* I. Concept and Numerical Simulation

4. QASER II. Simple Gain Calculation

5. QASER III. Coupled Electronic Oscillator Demo

6. Summary and Outlook

*Quantum Amplification via Superradiant Emission of Radiation
von Neumann Worries about Noise

John von Neumann asked what I was working on. After I told him about the maser and the purity of its frequency, he declared, “That can’t be right!”

To many physicists steeped in the uncertainty principle, the maser’s [noise] performance, at first blush, made no sense at all. Molecules spend so little time in the cavity of a maser, about one ten-thousandth of a second, [that it seemed impossible for the radiation to be so monochromatic]
The Laser Linewidth Is Due To Spontaneous Emission

\[ \langle (\Delta \Phi) \rangle^2 = A \Delta \tau \langle (\delta \phi) \rangle^2 \]

\[ \Delta \omega_{\text{laser}} = \frac{\langle (\Delta \Phi) \rangle^2}{\Delta \tau} \]

\[ \Delta \omega_{\text{laser}} = \frac{A}{\sqrt{n}} \]

One Spont. Emis.

A = Spont. Emis. Rate

Schawlow-Townes Phase Diffusion Linewidth
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Quantum Coherence

Density Matrix Definition

\[ |\Psi(\vec{r}, t)|^2 \]

\[ \Psi(\vec{r}, t) = a(t)\psi_a(\vec{r}) + b(t)\psi_b(\vec{r}) \]

\[ \vec{r}_{ab} = \int \psi_a^* \vec{r} \psi_b d\vec{r} \]

Atomic Dipole

\[ \vec{P} = \int e\vec{r} |\Psi(\vec{r}, t)|^2 d\vec{r} = e \vec{r}_{ab} a(t)b^*(t) + \text{c.c.} \]

Density Matrix

\[
\begin{pmatrix}
|a|^2 & ab^* \\
ab^* & |b|^2
\end{pmatrix} =
\begin{pmatrix}
\rho_{aa} & \rho_{ab} \\
\rho_{ba} & \rho_{bb}
\end{pmatrix}
\]

\[ \rho_{ab} = \text{Quantum Coherence} \]
Correlated Spontaneous-Emission Lasers: Quenching of Quantum Fluctuations in the Relative Phase Angle

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In quantum-beat and Hanle-effect experiments, spontaneous-emission events from two coherently excited states are strongly correlated. A doubly resonant laser cavity driven by such atomic configurations can have vanishing diffusion coefficient for the relative phase angle.

\[ < \hat{a}_1^+ (t) \hat{a}_2 (t) > = \rho_1 \rho_2 \exp (-D t), \]

where \[ D = \frac{1}{16} \left\{ \frac{\alpha_1}{\rho_1^2} + \frac{\alpha_2}{\rho_2^2} - \left( \frac{\alpha_{12} + \alpha_{21}^*}{\rho_1 \rho_2} \right) e^{-i\psi} \right\} + \text{c.c.} \]

Can be zero!

*See also PRA, 37, 1261 (1988).
Correlated Spontaneous Emission in a Zeeman Laser

-Michael P. Winters and John L. Hall\textsuperscript{(a)}

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CEL level diagram. Two laser transitions share a common level and the upper levels are coupled by an rf magnetic transition with an effective Rabi rate $\Omega$.

Summary: we have measured noise reduction 40% below the Schawlow-Townes limit in a HeNe laser due to the CEL effect. This noise reduction is in the relative phase of a two-mode laser and has potential implications for the design of optimally sensitive interferometers for gravitational wave detection.
LWI Concept I
(via quantum interference)

Quantum Photocell: Using Quantum Coherence to Reduce Radiative Recombination and Increase Efficiency

Marlan O. Scully

Optical Cavity

(a) Use of quantum coherence in ground state $b, c$ to cancel absorption (b) the use quantum coherence in the excited state $a, b$ to cancel emission

It is also possible to use the LWI concept to improve Quantum Photocell efficiency
Coherent amplification of an ultrashort pulse in a three-level medium without a population inversion

O. A. Kocharovsky and Ya. I. Khanin
Institute of Applied Physics, Academy of Sciences of the USSR

631 JETP Lett., Vol. 48, No. 11, 10 December 1988

Degenerate Quantum-Beat Laser: Lasing without Inversion and Inversion without Lasing

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Fano Coherence Dark State
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*Quantum Amplification via Superradiant Emission of Radiation
Quantum Amplification by Superradiant Emission of Radiation

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A laser generates light through stimulated emission of radiation and requires population inversion. Quantum interference can yield lasing without inversion. However, such phase-sensitive quantum amplification still requires some atomic population in the excited state. Here, we present a new kind of quantum amplifier based on superradiant emission of radiation (QASER) which does not need any population in the excited state!
The Super of Superradiance

Marlan O. Scully\textsuperscript{1,2} and Anatoly A. Svidzinsky\textsuperscript{1}

Cooperative single-photon emission from an atom ensemble will provide insights into quantum electrodynamics and applications in quantum communication.

\[ |\Psi\rangle = \frac{1}{\sqrt{N}} \left[ e^{i\vec{k}_0 \cdot \vec{r}_1} |\uparrow_1 \downarrow_2 \ldots \downarrow_N\rangle + e^{i\vec{k}_0 \cdot \vec{r}_2} |\downarrow_1 \uparrow_2 \ldots \downarrow_N\rangle + \ldots + e^{i\vec{k}_0 \cdot \vec{r}_N} |\downarrow_1 \downarrow_2 \ldots \uparrow_N\rangle \right] \]
Can rewrite the collective superradiant oscillation frequency as:

\[
\frac{\varphi}{\sqrt{\hbar \varepsilon_0 V}} \sqrt{\frac{\hbar v}{\varepsilon_0 V}} \sqrt{N_{at}} t = \sqrt{\frac{3}{4\pi}} \lambda^2 \gamma c \frac{N_{at}}{V} \equiv \Omega_a
\]

Defining the Rabi frequency \( \Omega_s(z, t) = \varphi \varepsilon_s(z, t) / \hbar \) we have our working equation:

\[
\left( \frac{\partial}{\partial t} + c \frac{\partial}{\partial z} \right) \Omega_s = i \Omega_a^2 \rho_{ab}
\]
Physics of QASER

Electromagnetic field and atoms are two coupled oscillators

Maxwell’s equation for electric field

\[
\left( \frac{\partial^2}{\partial t^2} - c^2 \Delta \right) \Omega = -2 \frac{\Omega_a^2}{\omega_{ab}} \frac{\partial^2 \rho_{ab}}{\partial t^2}
\]

Schrodinger equation for atoms

\[
\frac{\partial \rho_{ab}}{\partial t} + i \omega_{ab} \rho_{ab} = i \Omega (\rho_{bb} - \rho_{aa})
\]

Coupling between oscillators is nonlinear

Driving of atoms modulates coupling strength
**Analytical results**

Forward direction:

- $G = 0$

Backward direction:

- If Stark shift is suppressed then there is gain for $v_d > \frac{\Omega_a}{\sqrt{2}}$

  - Gain per unit time: $G_t = \frac{\Omega_a}{3\sqrt{2}} \left( \frac{\Omega_d}{\omega_{ab}} \right)^2$
  - Gain per unit length: $G_L = \frac{v_d}{c} \left( \frac{\Omega_d}{\omega_{ab}} \right)^2$
Numerical solution of Maxwell-Schrödinger equations

\[ \Omega_{ab} = 5.2 \nu_d, \quad \nu_d = 0.64 \Omega_a, \quad \Omega_d = \Omega_a, \quad L = 100 \frac{c}{\Omega_a} \]

\[ L = 100 \frac{c}{\Omega_a} \]

\[ \Omega_{l} \]

\[ \Omega_{drive} \]

Input pulse

Output pulse

Forward direction
\[ \omega_{ab} = 5.2 \nu_d, \quad \nu_d = 0.64 \Omega_a, \quad \Omega_d = \Omega_a, \quad L = 100 \frac{c}{\Omega_a} \]

Backward direction

Input pulse

Output pulse

<table>
<thead>
<tr>
<th>\Omega_l</th>
<th>120</th>
<th>100</th>
<th>80</th>
<th>60</th>
<th>40</th>
<th>20</th>
<th>0</th>
</tr>
</thead>
</table>

\[ \Omega_a t \]

\[ \Omega_{\text{drive}} \]

\[ \Omega_{\text{laser}} \]
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Quantum amplification by superradiant emission of radiation (QASER)

QASER does not need any population in the excited state

Amplification mechanism is the difference combination parametric resonance.
Comparison of atomic excitation mechanisms

Multiphoton resonant excitation

Single atom phenomenon

Multiphoton resonance with atomic transition frequency

\[ \nu_d = \frac{\omega_{ab}}{m} \]

\[ \rho_{aa} \approx \left( \frac{\Omega_d}{\omega_{ab}} \right)^{2m} (\omega_{ab} t)^2 \]

High frequency light is emitted in the direction of driving field

Collective parametric resonance

Collective effect

Resonance with collective frequency

\[ \nu_d > \frac{\Omega_a}{\sqrt{2}} \]

\[ \rho_{aa} \approx |\rho_{ab}(0)|^2 \exp \left( \frac{\sqrt{2}\Omega_d^2}{3\omega_{ab}^2} \Omega_a t \right) \]

Lasing occurs in the backward direction
**SIMPLE GAIN EQUATION**

\[
\dot{\Omega}_s = -i\Omega_a^2\rho_{ab} \\
\dot{\rho}_{ab} = -i\Omega_s^2(1 - 2\rho_{aa}) \\
\dot{\Omega}_s = (-i)^2\Omega_a^2(1 - 2\rho_{aa})\Omega_s \\
\dot{\rho}_{ab} = (-i)^2\Omega_a^2(1 - 2\rho_{aa})\rho_{ab} \\
\ddot{X} = -\Omega_a^2\left(1 - \left(\frac{\Omega_d}{\Delta}\right)^2\cos 2\Delta t\right)X
\]

\[
X = \Omega_s \text{ or } \rho_{ab} \quad \text{SAME EQUATION} \\
\text{SAME GAIN} \\
\text{Gain} = \frac{\Omega_a}{4}\left(\frac{\Omega_d}{\Delta}\right)^2
\]
Parametric harmonic oscillator (Mathieu equation)

\[ \frac{\partial^2 x}{\partial t^2} + \Omega_a^2 \left[ 1 - \delta \cos(\nu_d t) \right] x = 0 \]

\( \delta \ll 1 \)

Parametric resonance

If \( \nu_d = \frac{2\Omega_a}{m} \), \( m=1,2,3,... \) then oscillations exponentially grow with time:

For 1\(^{st}\) order resonance:

\[ x(t) \propto e^{Gt}, \quad G = \frac{\delta \cdot \nu_d}{8} \]

G – gain per unit time
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Systems with many normal modes $\omega_1, \omega_2, \omega_3, \ldots$

$\nu_d = \omega_2 + \omega_1$ ← Sum combination resonance

$\nu_d = \omega_2 - \omega_1$ ← Difference combination resonance

Example: Coupled parametric oscillators

\[ \ddot{x}_1 + \omega_0^2 x_1 - \Omega^2 x_2 = 0 \]
\[ \ddot{x}_2 + \omega_0^2 x_2 - \Omega^2 [1 + \delta \cos(\nu_d t)] x_1 = 0 \]

For 1st order resonance:

\[ G \propto \delta \cdot \Delta \omega \]

We solve equations numerically with

\[ \frac{\Omega^2}{\omega_0^2} = 0.25, \quad \delta = 0.4 \]
Experimental demonstration of difference combination resonance

\[ V(t) = V_0 \cos(\nu_0 t) \]

\[ \omega_1 = 196 \text{ kHz} \]

\[ \omega_2 = 222 \text{ kHz} \]

\[ \Delta \omega = 26 \text{ kHz} \]
\( \omega_1 = 196 \text{ kHz} \)
\( \omega_2 = 222 \text{ kHz} \)
\( \Delta \omega = 26 \text{ kHz} \)
\( \nu_d = 25 \text{ kHz} \)
\( V_0 = 0.9 \text{ V} \)
\[ V_A, \text{ Volts} \]

\[ \omega_1 = 196 \text{ kHz} \]
\[ \omega_2 = 222 \text{ kHz} \]
\[ \Delta \omega = 26 \text{ kHz} \]
\[ \nu_d = 26 \text{ kHz} \]
\[ V_0 = 0.9 \text{ V} \]
\omega_1 = 196 \text{ kHz} \\
\omega_2 = 222 \text{ kHz} \\
\Delta \omega = 26 \text{ kHz} \\
\nu_d = 27 \text{ kHz} \\
V_0 = 0.9 \text{ V}
\( \nu_d = 26 \text{ kHz} \)
Summary

• We present a new kind of amplifier (which we call the QASER) based on collective superradiant emission which does not need any population in the excited state and generates high frequency coherent radiation by driving an atomic ensemble with a much smaller frequency.

• The amplification mechanism of the QASER is governed by the difference combination resonance which occurs when the driving field frequency matches the frequency difference between two high frequency normal modes of the coupled light-atom system.

• To achieve gain one should suppress AC Stark shift of the atomic transition caused by the driving field.

• We also present an experiment which demonstrates the QASER amplification mechanism in an electronic circuit in the radio frequency region.