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The optical response of a double quantum well driven by two lasers: localization and low frequency generation.

Yuri Dakhnovskii¹, Raanan Bavli and Horia Metiu

Department of Chemistry² and Physics

University of California

Santa Barbara, CA 93106

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¹On leave from Institute of Chemical Physics, Russian Academy of Sciences, 4 Kosigyn st.,

117334 Moscow, Russia.

²Address for correspondence

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Electrons confined to a double quantum well and driven by a strong laser have interesting properties¹⁻¹⁰. An electron that has been, at a given time, localized in one of the wells will oscillate back and forth between them. Grossmann, Dittrich, Jung, and Hänggi¹⁻³ have shown that a laser with appropriate parameters can prevent this oscillation and keep the electron in the well in which it was initially located. The points (ω, E) (ω and E are the laser frequency and electric field amplitude) for which this electron localization takes place were called⁷ points of accidental degeneracy (AD). They are given by a simple equation, relating E to ω , whose validity has been established under a variety of conditions^{1-6,9}. The Fourier transform $\mu(\Omega)$ of the induced dipole, which determines light emission or absorption by the structure, also has unusual features. If (ω, E) are AD points $\mu(\Omega)$ has⁷⁻⁸ intense lines at the frequencies $2n\omega$, where n is an integer. This even-harmonic generation is intriguing: the Hamiltonian of the structure is symmetric and such emission is forbidden in all orders of a perturbation theory expansion in the field strength. Approximate equations for the intensity of these harmonics were derived by Ivanov, Corkum and Dieterich⁹⁻¹⁰. If the laser parameters are near an AD point $\mu(\Omega)$ has a very intense low frequency component⁷⁻⁸ whose frequency Δ can be tuned by changing E or ω , or by applying a voltage¹⁰ across the structure. This low frequency generation (LFG) is caused by the coherent oscillation of a major part of the electron density from one well to another. Equations for Δ are available⁹.

In this letter we study the response of an electron in a double quantum well driven by two lasers having the frequencies ω_1 and ω_2 . We show that the two lasers are capable of maintaining electron localization and generating low frequency radiation.

Numerical solutions of the time dependent Schrödinger equation for an electron in a double quantum well show that, under the conditions used here, the behaviour of the electron is adequately represented by a two level system. Because of this we have confined this study to a two level system whose parameters are chosen to represent a double quantum well. Analytical results are obtained by using an asymptotic method developed by Dakhnovskii *et al*⁹. They are valid when $v \equiv (\omega_2 - \omega_1)/\omega_2$ and $2\epsilon/\hbar\omega_1$ (2ϵ is the energy difference between the levels) are small.

We use the Hamiltonian:

$$H = \epsilon \{ |1\rangle\langle 1| - |2\rangle\langle 2| \} - \{ |1\rangle\langle 2| - |2\rangle\langle 1| \} \mu_{12} E(t) = \epsilon \sigma_z - \mu_{12} E(t) \sigma_x. \quad (1)$$

Here $|2\rangle$ and $|1\rangle$ are the ground and first excited states of the electron in the double well, respectively, and σ_x and σ_z are Pauli matrices. The zero of energy is halfway between the energy levels ϵ_1 and ϵ_2 , and $2\epsilon = \epsilon_1 - \epsilon_2$. The electric field in (1) is given by

$$E(t) = E_1 \cos(\omega_1 t) + E_2 \cos(\omega_2 t) \quad (2)$$

and the induced dipole is:

$$\mu(t) = \mu_{12} \langle \psi, t | \sigma_x | \psi, t \rangle, \quad (3)$$

where $|\psi, t\rangle$ is the wave function of the system at time t .

The equations of motion for $\mu(t)$ is⁹

$$d\mu(\tau)/d\tau = -(2\epsilon/\hbar\omega_1)^2 \int_0^\tau d\tau' \mu(\tau') \cos[F(\tau) - F(\tau')], \quad (4)$$

with

$$F(\tau) = (2\mu_{12}E_1/\hbar\omega_1) \sin(\tau) + (2\mu_{12}E_2/\hbar\omega_2) \sin[(1+\nu)\tau]. \quad (5)$$

We use the variable $\tau = \omega_1 t$.

To obtain information about $\mu(t)$, for the initial condition $\mu(\tau=0) = \mu_{12}$, we expand the right hand side of Eq. (4) in a power series in $(2\epsilon/\hbar\omega_1)$, identify the largest terms in this expansion and resume them. This procedure was used previously^{9,10} for the case when the system was driven by one laser. The result, for the two laser case, is

$$\mu(\tau) \cong \mu_{12} \cos[f(\tau)], \quad (6)$$

with

$$f(\tau) \cong (2\epsilon/\hbar\omega_1) \int_0^\tau d\tau_1 J_0 \left[\sqrt{e_1^2 + e_2^2 + 2e_1 e_2 \cos(\nu \tau_1)} \right], \quad (7)$$

and $e_i = 2\mu_{12}E_i/\hbar\omega_i$. This expression for μ contains only the terms that were resumed; the others are small, if $(2\epsilon/\hbar\omega_1)^2 \ll 1$, and are being ignored. The procedure gives the low frequency part of $\mu(t)$, hence the Eqs. (6) and (7) can be used to study localization (zero frequency) and low frequency generation.

If $\nu = 0$ the system is driven by one laser having the electric field intensity $E = E_1 + E_2$ and the frequency $\omega = \omega_1 = \omega_2$. For this case the Eqs. (6) and (7) become

$$\mu(t) \equiv \mu_{12} \cos[\Delta t] \quad (8)$$

with

$$\Delta = (2e/\hbar\omega_1)J_0[e] \quad (9)$$

and $e=2\mu_{12}E/\hbar\omega$. If $J_0(e) = 0$ the leading part of $\mu(t)$, given by Eq. (8), becomes time independent and equal to μ_{12} . This means that due to the laser action the system is, at all times, in one of the states $2^{-1/2} [|1\rangle \pm |2\rangle]$; in either state, the electron is localized in one of the wells. Thus, the AD points are given by $J_0(e) = 0$.

The induced dipole given by Eq. (8) oscillates with the frequency Δ . By choosing (ω, E) arbitrarily close to an AD point we can make Δ arbitrarily small. This is the low frequency generation (LFG) mentioned earlier in this article. LFG takes place because we work with laser parameters which are *almost* able to localize the electron. As the localization fails the whole electron density drifts slowly (on the time scale Δ^{-1}) from one well to another; this oscillation, of practically the whole charge over the large distance between the wells, has a very high dipole.

We examine next what happens when the electron is driven by two lasers. We consider that the electron is localized in one of the wells if

$$\mu(\tau) > 0.95 \mu_{12} \quad \text{for } \tau < 500. \quad (10)$$

Thus we require that the induced dipole is very close to the maximum value μ_{12} , which can be reached only if the greatest fraction of the charge density is localized in one of the wells. The definition used in prior work required $\mu(\tau) = \mu_{12}$ at all times. Complete localization for an infinite time is possible only in idealized models which ignore various, practically unavoidable, incoherent processes. For this reason we prefer the definition provided by Eq. (10).

$\mu(\tau)$ depends on the parameters e_1, e_2, v and $2e/\hbar\omega_1$. We will explore this large parameter space selectively. In Fig. 1 the dark regions show the parameter values, in

the (v, e_1) plane, for which the localization condition (10) is satisfied. The results for negative values of v are symmetrical to those for positive v . Since $v = 0$ means that only one laser acts on the system, the points along the $v = 0$ line are given by the condition⁹ $\cos[(2\varepsilon/\hbar\omega_1)J_0[e] \tau] < 0.95$ for $\tau < 500$. This gives small regions centered about the roots of the equation $J_0[e]=0$, that is, around the AD points of the one laser case. The size of these regions depends not only on the physical parameters of the system but on the numbers used in definition (10) as well. If we change 0.95 to a larger number (but less than one) or 500 to a longer time, the area will shrink.

The fact that for v near zero the electron localization takes place for parameters located in small regions, centered around the AD points for the system illuminated by one laser, is not surprising. However, the "fingers" appearing in the upper part of the figure, for larger values of v are unexpected. These regions are not continuously connected to the circles on the line $v = 0$. This means that they could not be obtained by perturbation theory in v .

In Fig. 2 we show the localization regions in the plane $\{e_1, e_2\}$. These form strips lined up along the zeros of the Bessel function J_0 . The missing points in the lower left part of the graph are real: we have searched for localization points there and found none.

Finally, in Fig. 3 we show the low frequency part of

$$\mu(\Omega) = \left| \int_{-\infty}^{+\infty} dt e^{-i\Omega t} W(t-t') \mu(t) \right| \quad (11)$$

$W(t-t')$ is a Gaussian window function and $\mu(\Omega)$ has peaks of Gaussian shape (i.e. the transform of the window function) centered at the frequencies of the Fourier components of $\mu(t)$. In Fig. 3 we give only the peak heights and positions. The parameters for which the spectrum has been calculated correspond to the cross in Fig. 1, which is a point near

the "finger" corresponding to the localization points.

In the system driven by one laser the choice of parameters near the AD points lead to low frequency generation⁷⁻⁹. This is also true in the two laser case: low frequency generation occurs for all points near those leading to localization. The physical reason for this is simple. At these points the lasers are almost capable of localizing the electron. As they fail the electron density drifts slowly from one well to another. This slow drift corresponds to a large dipole oscillating with a very low frequency δ . In this particular calculation $\delta = 1 \text{ cm}^{-1}$. The figure also shows what we have called, in our previous work⁷⁻⁹ shifted harmonics, which are Fourier components at the frequencies $n(\omega_2 - \omega_1) \pm \delta$. As the parameters approach the regions where localization occurs δ becomes smaller and ultimately goes to zero; furthermore, the shifted harmonics get closer and closer and ultimately collapse. We have plotted here only the low frequency part of the Fourier transform. At higher frequencies shifted harmonics centered around $n \omega_1$ and $n \omega_2$ are also present.

The low frequency part of the spectrum can be understood from Eqs.(6) and (7). Indeed, $f(\tau)$ given by Eq. (7) can be expanded as^[13]

$$f(\tau) \equiv (2\varepsilon/\hbar\omega_1)(J_0(e_1) J_0(e_2)\tau + \sum_{n=1}^{\infty} a_n \sin(nv\tau) / nv). \quad (12)$$

with $a_n = 2(-1)^n J_n(e_1) J_n(e_2)$. The leading term in Eq. (12) is

$$\delta\tau = (2\varepsilon/\hbar\omega_1)J_0(e_1) J_0(e_2) \tau, \quad (13)$$

which grows (when $J_0(e_1) J_0(e_2) \neq 0$) indefinitely with time, while the other terms are bound. Moreover, the amplitudes $J_n(e_1)J_n(e_2) / nv$ are small if v is not too close to zero. Introducing this in Eq. (6), using $\cos(a+b) = \cos(a) \cos(b) - \sin(a) \sin(b)$ repeatedly and retaining the largest term (the one containing cosines only) we obtain

$$\cos[f(\tau)] = \cos[\delta\tau] \cos[a_1 \sin(v\tau) / v] \dots \cos[a_n \sin(nv\tau) / nv] \dots \quad (14)$$

Using in this and the formula^[13]

$$\cos[a_n \sin(nv\tau) / nv] = J_0[a_n/nv] + 2 \sum_{m=1}^{\infty} J_{2m}[a_n/nv] \cos(mnv\tau). \quad (15)$$

we can obtain the Fourier components of $\mu(\tau) = \mu_{12} \cos[f(\tau)]$. We show here a few terms only:

$$\mu(\tau)/\mu_{12} = \prod_{n=1}^{\infty} J_0(a_n) \cos[\delta\tau] + J_1(a_1) \prod_{n=2}^{\infty} J_0(a_n) \{ \cos[(\delta+v)\tau] + \cos[(\delta-v)\tau] \} / 2 + \text{etc} \quad (16)$$

This equation is not exact. It is based on Eqs. (6) and (7), which are obtained by collecting the largest low frequency terms in $\mu(\tau)$. For this reason the formula does not contain the high frequency components of $\mu(\tau)$, such as, for example, the shifted harmonics at the frequencies $n \omega_1$. The formula predicts that the amplitudes of the terms with frequencies $(\delta+v)\tau$ and $(\delta-v)\tau$ are equal. The numerical results shown in Fig. 3 give nearly equal intensities as predicted.

Taking the limit $v \rightarrow 0$ in Eq. (12), which corresponds to one laser with the intensity parameter $e=e_1+e_2$ leads to

$$f(\tau) \rightarrow (2e/\hbar\omega_1) \{ J_0(e_1) J_0(e_2) + \sum_{n=1}^{\infty} 2 (-1)^n J_n(e_1) J_n(e_2) \} \tau. \quad (17)$$

The factor multiplying τ must equal Δ given by Eq. (9). Indeed this is the case since the expression in the curly brackets is equal to $J_0(e_1+e_2)$ ¹⁴.

In this article we have shown that an electron confined to a double quantum well and driven by two lasers whose frequencies are closed to each other, can be localized or forced to emit or absorb low frequency radiation. In the case when the two frequencies are almost equal (i.e. when $v = (\omega_2 - \omega_1)/\omega_1$ is almost zero), the present results are a simple extension of those obtained in the case when the electron is driven by one laser. As v is increased the localization is no longer possible until higher values of v are

reached; then the localization is again possible in extended regions of the parameter space. These regions are not an analytic extension of those obtained for a one laser system. Our conclusions follow from analytical results which give the leading low frequency contribution to the induced dipole. Extensive comparisons with numerically exact calculations show that the analytical results are accurate as long as $2\epsilon/\hbar\omega_1 \ll 1$. In real system various incoherent processes and electron escape from the well limit the time over which localization can be observed.

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References

1. F. Grossmann, T. Dittrich, P. Jung, and P. Hänggi, Phys. Rev. Lett. **67**, 516 (1991)
2. F. Grossmann, T. Dittrich, and P. Hänggi, Physica **B 175**, 293 (1991)
3. F. Grossmann and P. Hänggi, Z. Phys. **B 85**, 315 (1991)
4. D. Neuhauser, Coherent Destruction of Tunneling-Physical Origin (preprint 1992)
5. M. Holthaus, Phys. Rev. Lett. **69**, 351 (1992)
6. J.M. Gomez Llorente and J. Plata, Phys. Rev. A **45**, R6958 (1992)
7. R. Bavli and H. Metiu, Phys. Rev. Lett. **69**, 1986 (1992)
8. R. Bavli and H. Metiu, Phys. Rev. A (in print)
9. Y. Dakhnovskii and H. Metiu, Phys. Rev. A (submitted)
10. Y. Dakhnovskii, R. Bavli and H. Metiu, The response of an electron in a biased double well to a strong laser: delocalization and low frequency generation (preprint)
11. M.Y. Ivanov and P.B. Corkum, Phys. Rev. A (in press)
12. M.Y. Ivanov, P.B. Corkum and P. Dieterich, Phys. Rev. Lett. (submitted)
13. M. Abramowitz and I.A. Stegun, Handbook of Mathematical Functions, (Dover Publications, New York, 1965), Eq. 9.1.43
14. I.S. Gradshteyn and I.M. Ryzhik, Tables of Integrals, Series and Products, (Academic Press, New York, 1965), 4th Edition, Eq. 8. 531, p. 979

Figure Captions

Fig. 1. The dark areas show those regions [given by Eqs. (6) and (7)] in the parameter space (ν, e_1) , for which electron localization occurs. We used $e_1=e_2$ and $2\varepsilon/\hbar\omega_1 = 0.1$ and $\omega_1 = 100 \text{ cm}^{-1}$.

Fig. 2. The dark areas show those regions [given by Eqs. (6) and (7)] in the parameter space (e_1, e_2) for which electron localization occurs. We used $2\varepsilon/\hbar\omega_1 = 0.1$, $\nu = 0.1$ and $\omega_1 = 100 \text{ cm}^{-1}$.

Fig. 3. The low frequency part of the Fourier spectrum of the induced dipole [see Eq. (11)] for the point in the parameter space marked by x in Fig. 1 ($e_1=e_2=4.5$, $2\varepsilon/\hbar\omega_1 = 0.1$, $\nu = 0.07$). The spectrum has peaks at $n\nu \pm \delta$ where $\delta = 1 \text{ cm}^{-1}$.

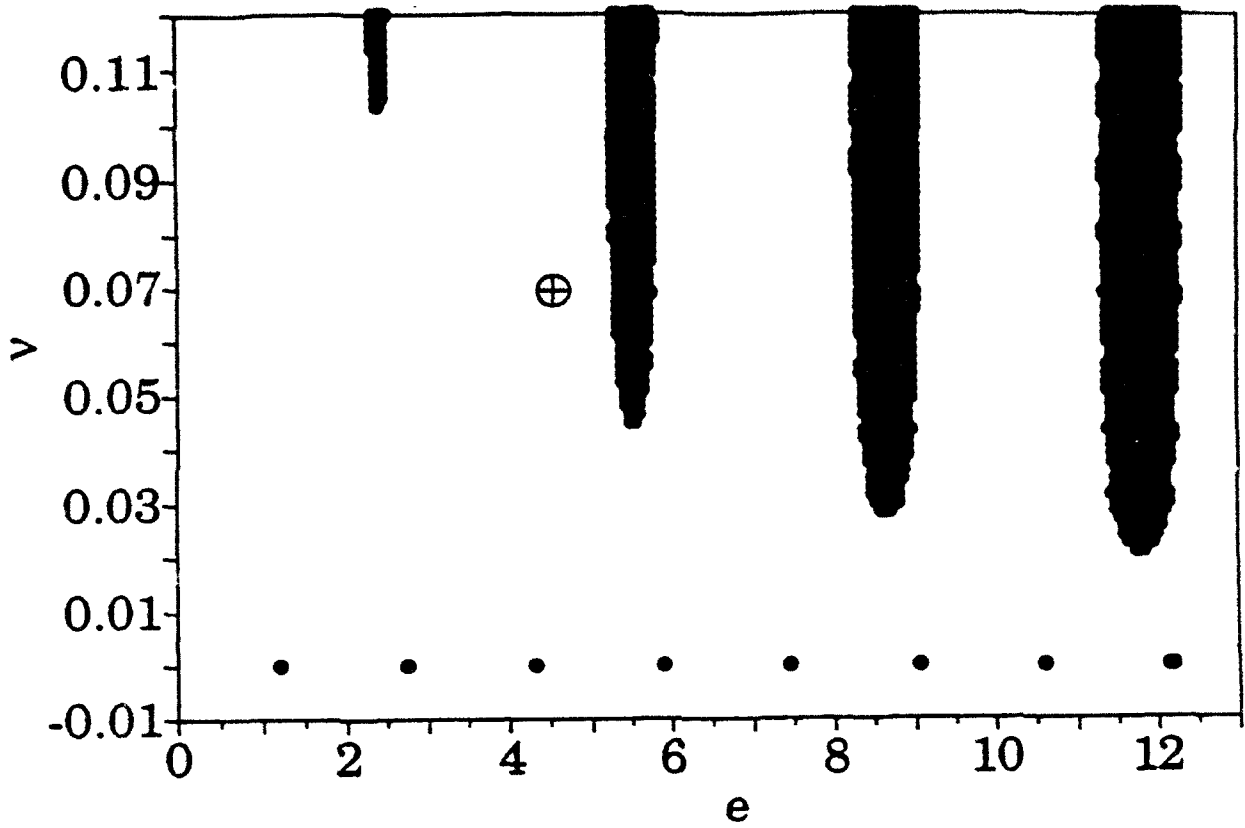


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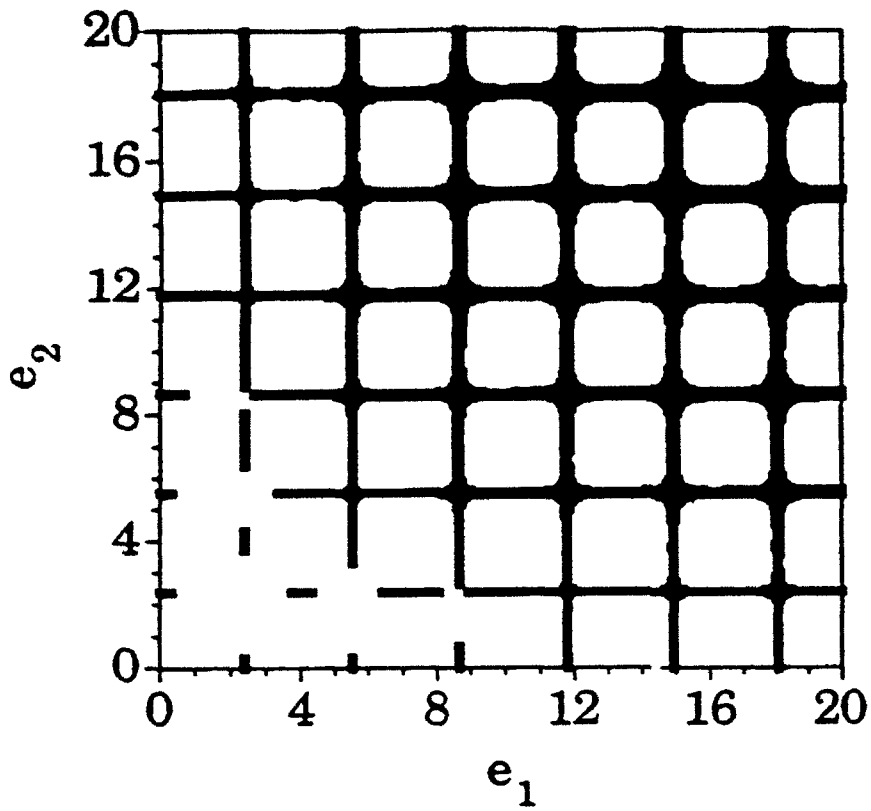


Fig. 2
 Diagram of Basis and Metric

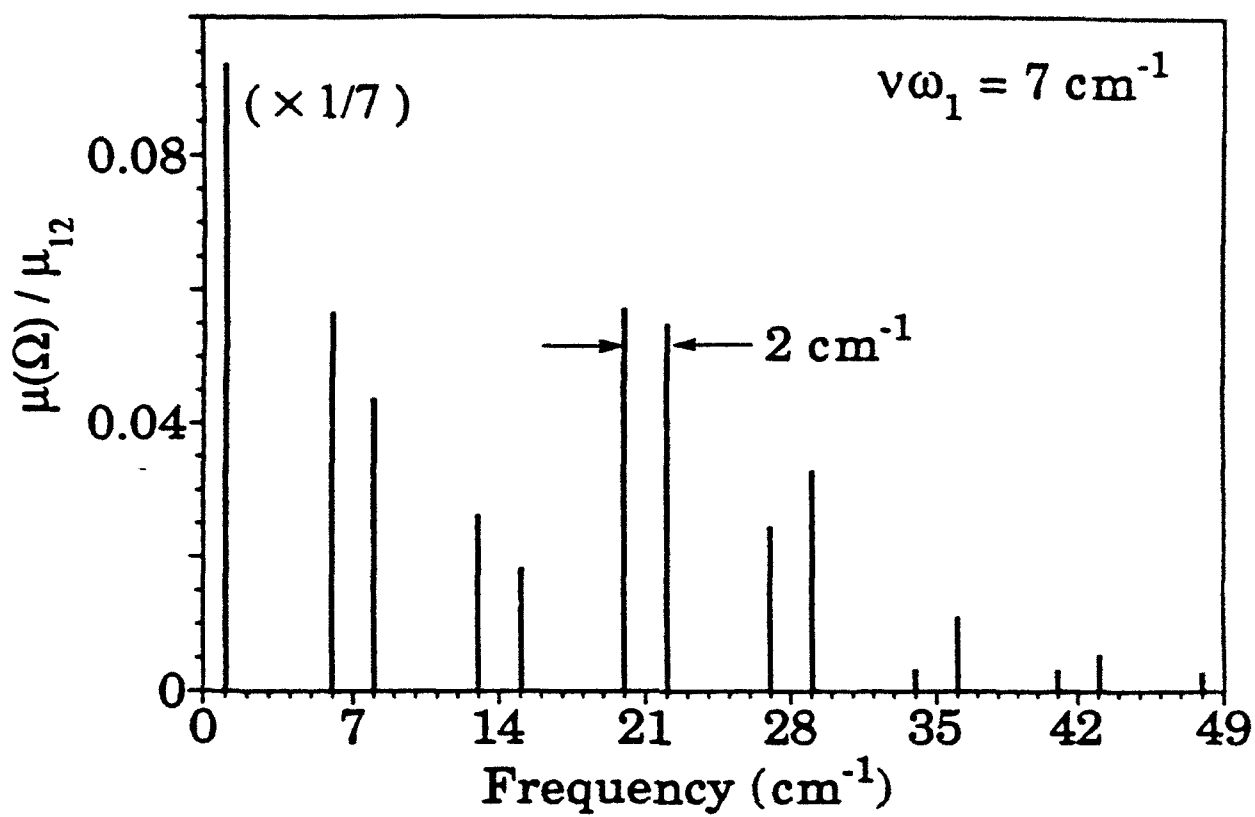


Fig. 5 Josephson Bands and Noise

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