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Spectral and intensity dependence on dipole localization in Fabry–Perot cavities

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Data is presented on the characteristics of light emitted from localized dipoles contained in Fabry–Perot cavities. The cavities consist of AlGaAs semiconductor with the dipole localization achieved using GaAs quantum wells. Experimental data shows that the standard assumption of the spectral width of a cavity mode as having some fixed relationship to the photon lifetime in the cavity is an approximation which only becomes valid for dipoles throughout the cavity. Also, intensity differences are measured out either side of a cavity even when symmetrical mirrors are used. The intensity difference depends on the precise dipole position. Both the spectral and intensity differences can be derived from theory using a model which accounts for interference between coherent spontaneous wavepackets emitted in opposite directions from individual emission events.

The Fabry–Perot cavity has become a basic building block of many optical devices including the laser. Understanding the optical characteristics of the cavity, therefore, is useful in analyzing various aspects of active device operation. For example, Hakki and Paoli have presented a now widely used technique by which optical gain in the semiconductor can be deduced through the measurement of the ratio of transmission peak to valley ratio in the Fabry–Perot transmission modes of light emitted from the cavity.[1] Although the transmission characteristics of the Fabry–Perot cavity have been known for a long time, it is also appreciated by some workers that the emission characteristics for a dipole contained in such cavities represent a complex interaction between the emitted light and the optical cavity. In this letter we show that the typical assumption of the spectral width of Fabry–Perot cavity modes as depending simply on the photon lifetime in the cavity is an approximation which becomes valid for the case of emitting dipoles distributed over a significant region of the cavity, but one which can be in considerable error for the case when the dipoles are localized. Moreover, we show that even for an otherwise symmetrical Fabry–Perot cavity, the emitted intensity from either side of the cavity can also have a strong dependence on the precise dipole placement in the cavity.

If a single, stationary, emitting dipole is considered, one may imagine its emission process as proceeding in a few different ways. On the average, that is the average over many dipoles or many emission events from a single dipole, the dipole is expected to emit in a manner which reproduces the classical donut-shaped far-field radiation pattern. On the other hand, for the single emission event one may question whether the actual emission process may in fact be more directional. One way to test the directionality of the emission is to interfere light emitted in different directions, with a Fabry–Perot cavity, for instance, which will alter the spectrum measured in one direction. For a collection of spatially distributed dipoles, this method is not effective due to averaging over many dipole positions with respect to a fixed boundary condition of the reflector. However, when the dipoles are localized at one position with respect to the reflector boundary, the measured emission spectrum contains information on the directionality of the emission. Assuming that the single emission event from the dipole does occur more or less isotropic in space (with a donut shaped far-field), the spectrum from a localized dipole in the Fabry–Perot cavity will result from two coherent, counterpropagating wavepackets traveling around the cavity, and partially transmitted each time one or the other encounters a reflector. The field amplitude of the wavetrain emitted from a single dipole out the L_1 side of the cavity (Fig. 1) is given by the infinite series.

$$\begin{aligned}E_{L_1}(t+L_1/c) &= \tau WP(t)+\tau\rho WP(t-2L_2/c)\\ &\quad +\tau(\rho^2)WP(t-2L/c)\\ &\quad +\tau\rho(\rho^2)WP(t-2L_2/c-2L/c)+\cdots, \quad (1)\end{aligned}$$

where τ is the field transmission through R, ρ is the field reflectivity for R, and $WP(t)$ is the electric field amplitude versus time for a single emission event. We assume that ρ

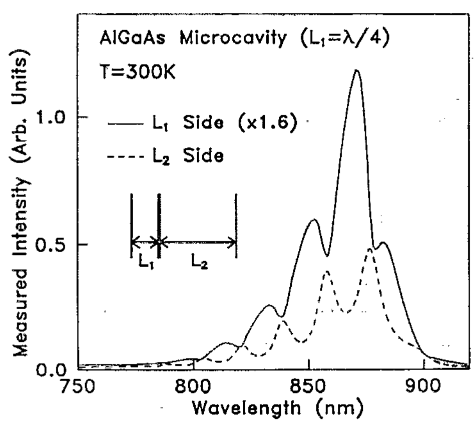

FIG. 1. Measured intensity vs wavelength for light emission from a 5μm-long Fabry–Perot cavity with dipoles localized $\lambda/4$ away from an air-semiconductor reflecting boundary.

and τ are purely real for convenience. The spectrum of the pulsed, double wavepackets wavetrain emitted from the cavity is found from the Fourier transform of the infinite series of Eq. (1). For a single dipole emission event the spectral intensity as a function of frequency from one side of the cavity is given as

$$|E_{L_1}(\omega)|^2 = T|WP(\omega)|^2[1+R^2-2R\cos(2\omega L/c)]^{-1} \times[1+R+2R^{1/2}\cos(2\omega L_2/c)], \qquad (2)$$

where L_1 is the dipole distance from the emitting mirror, E_{L_1} refers to the field emitted from the L_1 side of the cavity, R is the reflectivity of the cavity mirrors (taken as ρ^2), T represents the intensity transmission through R (taken as τ^2), L is the cavity length ($L=L_1+L_2$), and $|WP(\omega)|$ is the frequency spectrum of the field of an initial wavepacket inside the cavity. The term $[1+R+2R^{1/2}\cos(2\omega L_2/c)]$ represents interference in the pulse train emission due to opposite propagating wavepackets inside the cavity. A similar term containing L_1 exists for the pulse train which makes up $|E_{L_2}(\omega)|^2$. Equation (2) suggests that for isotropic emission, both spectral and intensity differences occur for emission from either side of the otherwise symmetrical Fabry–Perot cavity. The last term in brackets on the right of Eq. (2) will play a significant role in determining the spectral width and intensity of the emission from the cavity. For uniformly distributed positions in the cavity, this term will average to a constant giving the typical Fabry–Perot transmission modes which overlap $|WP(\omega)|^2$ as the emission spectrum.

The Fabry–Perot cavities used in our studies have been fabricated from epitaxial AlGaAs-GaAs heterostructures grown using metalorganic chemical vapor deposition. Fabrication procedures have been described previously,[2] and result in otherwise symmetrical cavities except for the position of a single GaAs quantum well (QW) used to localize the emitting dipoles. In the processing, the GaAs substrate is selectively removed to leave a free standing thin semiconductor film of several microns thickness. Data from two AlGaAs structures, in particular, are presented here. The AlGaAs cavities have a length of $L=5$ μm, and use air-semiconductor boundaries as each reflector. The precise QW placement is shifted in each of the two cavities, being an effective $\lambda/4$ distance from one of the air-semiconductor reflectors in one cavity and $\lambda/2$ distance from the reflector in the other. The opposite reflector in the cavities is then $\approx 18\lambda$ away from the QW. Consistent with Eq. (2), this small shift in QW position between the two cavities is found to have a significant impact on both the frequency spectrum and relative intensity of spontaneous emission from either side of the otherwise symmetrical Fabry–Perot cavities.

Figure 1 shows the measured emission spectra from both sides of the AlGaAs cavity with the QW at $\lambda/4$ away from one of the cavity reflector boundaries. The spectral data is measured by exciting the cavity and QW region with a 6328 Å He-Ne laser. Care is always taken to verify that the measured spectrum is insensitive to pump power to insure that only spontaneous emission is measured, but

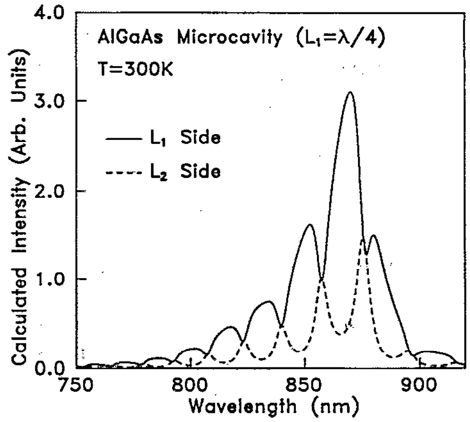

FIG. 2. Emission intensity vs wavelength calculated from Eq. (1), and using the dipole distribution of a GaAs QW, for the cavity with dipoles localized $\lambda/4$ away from one of the reflecting boundaries (corresponding to measured curves of Fig. 1).

the 30% reflectivity of the cavity along with the gain of the single 300 Å QW are also much too low for stimulated emission to be significant. The solid curve is the measured emission spectrum from the $L_1(\lambda/4)$ side (pumping from the L_2 side), as designated in Fig. 1, while the dashed curve is the measured spectrum from the $L_2(\sim 18\lambda)$ side. Significant differences occur between the two spectra in terms of modal position, modal spectral width, and overall intensity. Note that the solid curve has been multiplied by a factor of 1.6 to aid in the comparison of Fig. 1 (measured curves) with the calculated curves of Fig. 2. However, a significant intensity difference is in fact measured in the overall output intensity between the output emission from the L_1 side as compared to that of the L_2 side, and is discussed further below. Calculated spectral curves generated from Eq. (2), using a calculated energy dipole distribution for the GaAs QW to obtain $|WP(\omega)|$, is shown in Fig. 2 for the cavity with $L_1=\lambda/4$. Excellent agreement is found between the calculated curves of Fig. 2 and the measured spectral curves of Fig. 1.

Figure 3 shows spectral data for the second AlGaAs Fabry–Perot cavity in which the GaAs is placed $\lambda/2$ away from one of the air-semiconductor reflectors. Again the L_1 side emission is multiplied by a factor of 1.6 for comparison with the calculated curves of Eq. (2). The distinction in spectral differences between the L_1 side and L_2 side emission being the peak to valley ratio in the spectral modulation. Again excellent agreement is found between the measured spectral curves of Fig. 3 and the calculated curves shown in Fig. 4. For this cavity with a $\lambda/2$ spacing, a higher intensity is calculated and measured for emission from the L_2 side as opposed to the L_1 side. This is opposite of that of the intensity ratio for the cavity with the $\lambda/4$ spacing (Figs. 1 and 2).

The calculated ratios of spectrally integrated intensities measured from either side of the cavity structures are $I_{L_1}/I_{L_2}=3.1$ for the $L_1=\lambda/4$ cavity, and $I_{L_1}/I_{L_2}=0.71$ for the $L_1=\lambda/2$ cavity. The measured integrated intensity ratios are $I_{L_1}/I_{L_2} = 1.9$ for the $L_1=\lambda/4$ cavity, and

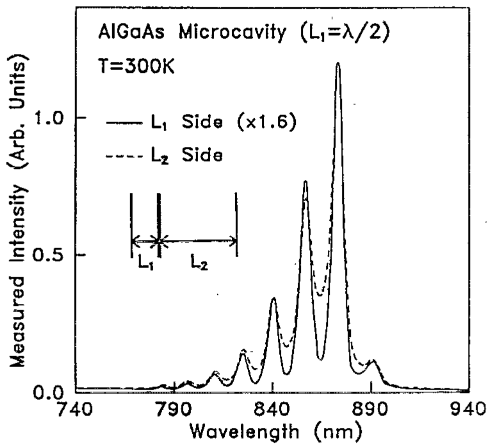

FIG. 3. Measured intensity vs wavelength for light emission from a 5-μm-long Fabry–Perot cavity with dipoles localized $\lambda/2$ away from an air-semiconductor reflecting boundary.

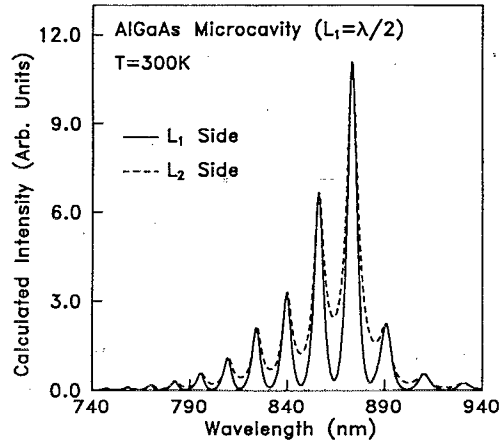

FIG. 4. Emission intensity vs wavelength calculated from Eq. (1), and using the dipole distribution of a GaAs QW, for the cavity with dipoles localized $\lambda/2$ away from one of the reflecting boundaries (corresponding to measured curves of Fig. 3).

$I_{L_1}/I_{L_2}=0.44$ for the $L_1=\lambda/2$ cavity. For both measured ratios, the light emission from the L_1 side can be viewed as being reduced by a factor of ~ 1.6 compared to the expected intensity relative to the L_2 side. This is most likely due to the nonuniform pumping from the L_2 side of the cavity, in which carriers must diffuse several μm to reach the QW. However, the quantitative behavior between the two structures is as expected from Eq. (2).

In conclusion we note that Einstein has used a thermodynamic argument to suggest that the single spontaneous emission event must occur with a well defined direction.[3] On the other hand the interpretation of the spontaneous emission wavepackets in terms of quantum mechanical probability amplitudes is presently, it seems, unclear.[4,5] In the experimental work we have presented here it does seem clear that interference effects which arise outside the Fabry–Perot cavity for oppositely emitted wavepackets from the single emission event, must be considered to properly account for the measured cavity emission spectrum and intensity.

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