Physics and Device Applications of Optical Microcavities

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Optical microcavities are resonators that have at least one dimension on the order of a single optical wavelength. These structures enable one to control the optical emission properties of materials placed inside them. They can, for example, modify the spatial distribution of radiation power, change the spectral width of the emitted light, and enhance or suppress the spontaneous emission rate. In addition to being attractive for studying the fundamental physics of the interaction between materials and vacuum field fluctuations, optical microcavities hold technological promise for constructing novel kinds of light-emitting devices. One of their most dramatic potential features is thresholdless lasing. In this way and others, controlled spontaneous emission is expected to play a key role in a new generation of optical devices.

Einstein pointed out in 1917 that an atom can radiate a photon in two different ways (*1*). The first is spontaneous emission, whereby the excited atom spontaneously emits a photon without any influence from outside photons. The other is stimulated emission, in which external photons induce or stimulate the emission of a new photon from the atom. Before the invention of the laser in 1960 (*2*), only light derived from spontaneous emission processes was available for laboratory (and home) use. After 1960, attention focused on stimulated emission, the essence of laser action. Ultrashort optical pulses of picosecond and femtosecond duration, light sources with a linewidth of only a few hertz, and ultrahigh-power lasers producing terawatts are remarkable examples of advanced laser science. These developments are all the result of the coherent laser process in which stimulated emission controlled by a "cavity" dominates the overall process of light emission. However, spontaneous emission has long been widely believed to be uncontrollable. In the last decade, however, marked progress has been achieved in controlling spontaneous emission with the use of wavelength-sized cavities. This research field is now called cavity quantum electrodynamics (cavity QED) (*3*). The highly developed state of laser technology has made possible the precise experiments required for this spontaneous emission research. In cavity QED, much work has been directed toward studying the fundamental physics of the interaction of matter with vacuum field fluctuations. Originally, many experiments were carried out in the microwave region by using Rydberg state atomic beams (*4–7*). More recently, attention has turned to the optical regime in experiments in which atomic beams (*8–10*), organic dyes (*11*, *12*), and semiconductors (*13–15*) are used.

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Controlling spontaneous emission is also desirable for device applications (*14–19*). Of particular interest is the concept of a "thresholdless laser" proposed by Kobayashi *et al.* (*16*). In a conventional laser, only a small portion of the spontaneous emission couples into a single state of the electromagnetic field controlled by the laser cavity (that is, the cavity resonant mode formed by the cavity mirrors); the rest is lost to free space modes (that is, it radiates out the side of the laser). This is one of the essential mechanisms behind the occurrence of laser oscillation "threshold" behavior; intense stimulated emission output can be obtained only above a threshold input power that can overcome the spontaneous emission loss to free space modes.

The idea of a thresholdless laser is simple. When all spontaneously emitted photons are confined in a cavity whose dimensions are on the order of a single wavelength, loss to the free space mode is eliminated. Then the clear boundary between spontaneous and stimulated emissions inside the cavity is eliminated; this can cause the disappearance of a threshold in the input-output curve (see below). Recent demonstrations of nearly thresholdless laser operation (*20*, *21*) with the use of condensed materials offer technological promise for constructing a new type of laser devices with ultralow power consumption.

Altering Spontaneous Emission

It is often easier to understand how spontaneous emission can be altered from a quantum mechanical viewpoint rather than from a classical viewpoint (*19*, *22–24*). In the framework of Fermi's golden rule, the effect of optical confinement in one or more dimensions is a rearrangement of the usual free space density of photon states (mode density). The mode density at some frequencies would be increased, whereas at others it would be decreased. Furthermore, the increase or decrease would be accompanied by a spatial redistribution of mode density. Thus, if a photon-emitting medium is introduced into such a cavity, both the rate and the direction of emission would be altered. In the sense that they confine quantum mechanical waves to a limited space and change the density of states, microcavities are analogous to semiconductor quantum-confinement structures. Classically, the mode density increase (or decrease) can be understood to be the resonant enhancement (or antiresonant suppression) of the emitted electromagnetic field in the cavity. Thus, the enhanced (or suppressed) spontaneous emission is the self-reaction process of an oscillating dipole.

First, let us consider the change in the spatial distribution of the spontaneous emission intensity caused by a microcavity. The discussion focuses on planar cavity structures (one dimension of optical confinement) because most of the experiments performed in the optical region have been carried out with such planar cavity structures. The physical system of a planar microcavity is depicted in Fig. 1A. The dipole is situated at the midpoint of the cavity (at the origin of the xyz coordinates). For simplicity, a pair of virtual reflectors, which show no dependence on the reflectivity of the incident angle but which have a finite transmission loss, are assumed. Then, the spatial radiation pattern of the spontaneous emission is calculated by a classical method. The curves depicted in Fig. 1, B to D, show the radiation intensity distributions of a monochromatic dipole located in free space, in a half-wavelength ($d = \lambda/2$) cavity, and in a $d = 7\lambda/2$ cavity, respectively. It is assumed here that the electric dipole is oriented parallel to the y axis and that the mirror reflectivity R is 0.95. The radiation intensity is mapped in the y-z plane. The distance between a point on the curve and the origin corresponds to the emission intensity, and free space emission intensity in the z axis direction is normalized to be unity. The emission intensity in the cavity axis direction is enhanced by a factor of

$[2(1 + R)/(1 - R)] \approx 80$ in a resonant cavity. Furthermore, only a single radiation cone, which is strongly directed into the cavity axis, is formed for a planar microcavity of $d = \lambda/2$. Thus, there is strong confinement of the spontaneous emission into a single cavity-controlled mode. Even if randomly oriented dipoles are assumed instead of single axis–oriented dipoles, the characteristics described do not change significantly. However, when half of the dipole's wavelength, $\lambda/2$, is slightly smaller than the mirror separation d, the emission cone spreads off the cavity axis. On the other hand, if $\lambda/2$ is larger than d, the emission intensity is decreased in all directions. When one considers condensed materials such as semiconductors or dyes, one has to remember that the emission is broadband rather than monochromatic; that is, there are many frequency components. Thus,

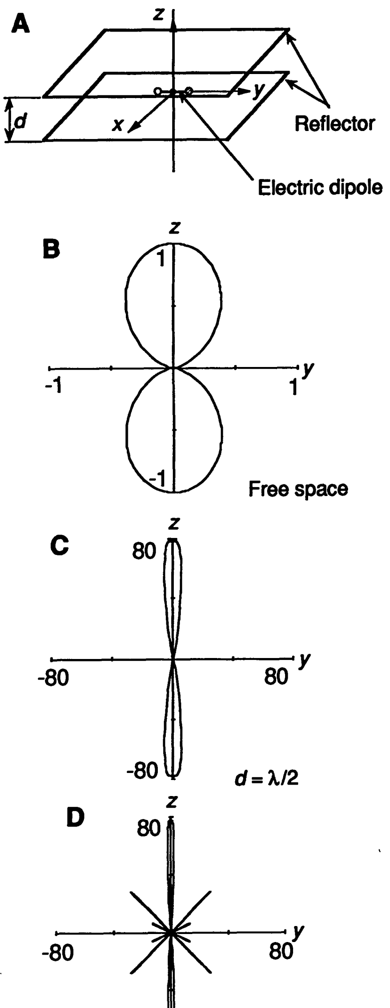

Fig. 1. (**A**) Physical setup of the planar mirror microcavity. Emission intensity distribution patterns of electric dipoles directed along the y axis in (**B**) free space, (**C**) $\lambda/2$ cavity, and (**D**) $7\lambda/2$ cavity; views of the intensity lie in the y-z plane.

even with a $\sim\lambda/2$ cavity, the directionality of the spontaneous emission in the cavity axis would deteriorate.

A planar microcavity can induce changes not only in the distribution of the spontaneous emission intensity but also in the spontaneous emission rate. In Fig. 2, the spontaneous emission rate is shown for single axis–oriented dipoles inside a planar microcavity similar to that shown in Fig. 1A. The spontaneous emission rate is normalized to the free space rate. With a planar cavity having a mirror separation larger than $\lambda/2$, the potential increase or decrease in the spontaneous emission rate is at most a factor of 3 or 2, respectively; these values are almost the same even if we assume that a broadband emission material such as GaAs is used (*19*). More drastic changes are, however, expected in two or three dimensionally confined microcavities. For example, a wave guide having a $\sim\lambda/2$ by $\lambda/2$ cross section can induce complete suppression of spontaneous emission or enhancement of the spontaneous emission rate by more than a factor of 10 (*19*). This result shows the importance of restricted dimensionality in altering the spontaneous emission rate. In other words, the confinement of spontaneously emitted photons into a smaller volume can induce a larger change in emission rate.

In the optical domain, it may be necessary to use multilayer dielectric stacks instead of metals for the highly reflective mirrors. These dielectric reflectors have a large penetration depth and a very limited reflection bandwidth, as well as a rather strong angle dependence of the reflectivity. Thus, the above discussion gives us only qualitative insights into the features of spontaneous emission in optical microcavities. Recently, a few investigators have tried to calculate how the spontaneous emission changes with more realistic optical microcavity structures made by dielectric multilayer reflectors (*25, 26*); further progress in these theoretical works is important for quantitative understanding of real world microcavities.

Spontaneous Emission Experiments with Optical Microcavities

Although many successful cavity QED experiments have been carried out in the microwave region, experiments in the optical region have proven more difficult. The reason is that the dimension of the cavity should be of the micrometer or submicrometer scale in order to produce strong cavity effects. On this scale it is then appropriate to use condensed materials as light emitters instead of atomic gases that can be used with larger microwave cavities.

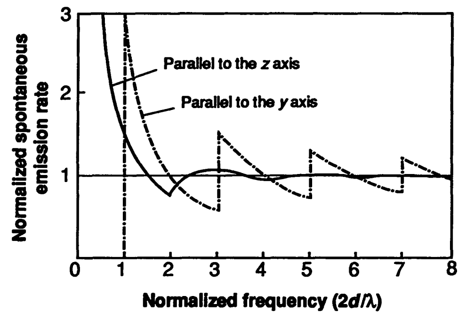

Fig. 2. Change in the spontaneous emission rate of an electric dipole in a planar microcavity as a function of the dipole oscillation frequency for two different dipole orientations. The spontaneous emission rate is normalized by the free space value, and the normalized frequency is given by the ratio $2d/\lambda$.

This approach in turn sacrifices the spectral purity of the atomic optical transitions and makes quantitative comparison with theory difficult. In addition, only planar cavity structures, that is, one dimensionally confined optical microcavity structures, are available at present for controlling spontaneous emission. Dielectric microspheres (*27, 28*) have been shown to work as laser cavities of high quality factor (Q) for certain modes, but in these structures a large portion of the spontaneous emission can be radiated into free space without seeing strong cavity effects.

The first report of the altering spontaneous emission with a fabricated microcavity structure was made by Drexhage (*29*). His microcavities consisted of Langmuir-Blodgett (LB) films deposited on metal mirrors. The use of an LB film offers the considerable advantage of allowing the thickness to be controlled with monomolecular layer precision while simultaneously yielding reproducible, high-quality films. Dye molecules were embedded in single monolayers of LB films and were optically excited. Drexhage observed dramatic modifications of the radiation distribution patterns induced by the presence of the microcavities. A clear change in spontaneous emission lifetime was not observed, however, because Q was not high enough. He also encountered the problem of charge transfer to a metal mirror. More recently, an LB film microcavity experiment has been carried out by using pairs of highly reflective dielectric mirrors (*12*). In this experiment, decreases and increases of the spontaneous emission rate of a factor of 2 were observed depending on the mirror separation.

Progress in crystal growth technology for ultrathin semiconductors has also made it possible to fabricate monolithic semiconductor microcavity structures. This approach is quite important from a device application point of view because semiconductors can be excited electrically rather

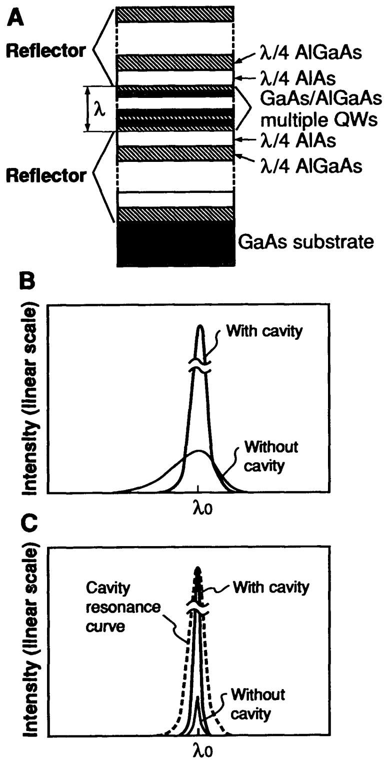

Fig. 3. Schematic view of (**A**) a GaAs QW microcavity structure, and spontaneous emission spectra observable along the cavity axis for (**B**) band-to-band emission and (**C**) an excitonic transition at low temperature.

than optically with an external laser. By using molecular beam epitaxy (MBE) technology, several groups have fabricated microcavities containing GaAs quantum wells (QWs) combined with monolithic layered AlGaAs/AlAs reflectors (*14, 15*). Similar structures are used in vertical cavity surface-emitting semiconductor lasers (VCSELs), independently of the purpose of spontaneous emission control (*30–33*).

The structure of a typical monolithic microcavity is shown in Fig. 3A. A room-temperature emission spectrum observable in the cavity axis direction when $d \sim \lambda$ is schematically shown in Fig. 3B. The bandwidth narrowing due to the cavity resonance restriction is shown accompanied by a marked intensity enhancement within the cavity resonance curve. Even the spectrally integrated emission intensity can be increased by the microcavity. This occurs when only one Fabry-Perot cavity resonance curve exists within the material's emission bandwidth (*18*). However, when $d < \lambda/2$, emission is significantly suppressed overall because of the absence of allowed emission modes within the material's bandwidth. These features of a QW microcavity have been observed experimentally (*14*). Similar characteristics were also observed in the LB film microcavity experiment (*12*).

When an experiment is performed at low temperature, a narrow-band excitonic transition can dominate the spontaneous emission process instead of the broad band-to-band electron hole recombination. In this situation, a Fabry-Perot resonance curve can cover the entire spectral width of an excitonic emission. The intensity change of the emission spectrum under this condition is shown in Fig. 3C. In this case, the excitonic emission can be regarded as quasi-monochromatic, and the emission power along the cavity axis direction is considerably increased. This intensity increase in the spectral domain corresponds in the spatial domain to a concentration of the spontaneous emission power into the cavity axis as shown in Fig. 3C. These features of an excitonic emission in a monolithic microcavity have also been observed experimentally (*15*).

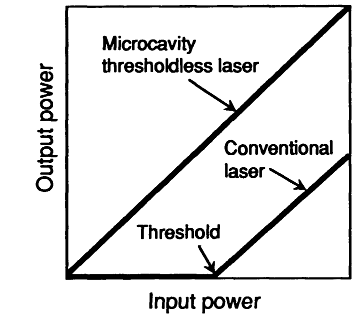

Fig. 4. Schematic of input-output characteristics of a conventional laser and a microcavity thresholdless laser.

The Thresholdless Laser

Controlling spontaneous emission can also lead to remarkable changes in the oscillation properties of lasers. The most dramatic result of controlling the spontaneous emission may be thresholdless laser oscillation (*16*). In the mode point of view, most of the excited atoms in a conventional large-size cavity are coupled to free space modes, even though there is only one cavity mode within the emission bandwidth. In other words, most of the spontaneous emission radiates out the side of a conventional laser cavity. In that situation, the cavity mode photon number can increase rapidly only above "threshold" as a result of stimulated emission. Thus, a sharp break appears at the threshold point in the input-output curve. However, in the ideal microcavity, all of the photons emitted couple into the single cavity resonance mode. Therefore, with increased pumping, the emission process gradually changes from spontaneous to stimulated emission without a sharp turn (threshold) in the input-output curve. These behaviors are schematically plotted on a linear scale in Fig. 4.

It may be useful to show the result of a calculation for static properties of microcavity laser oscillation (*18*) in order to gain more quantitative insight. Figure 5 depicts calculated results for gain (A) and output power (B) versus input power for a single mode microcavity laser (on a logarithmic scale). The parameter β corresponds to the solid angle fraction of spontaneous emission coupled into the cavity mode compared to that lost to free space. Other parameters used are basically those of a conventional diode laser, although a four-level medium approximation is assumed for simplicity. When β is small, clear thresholds are observed in the input-output curves. In conventional semiconductor laser devices, β ranges from 10^{-6} to 10^{-5} per cavity mode. The threshold becomes washed out as β increases and disappears for $\beta = 1$; the device works as a "thresholdless laser," as long as only the output versus input characteristics are considered.

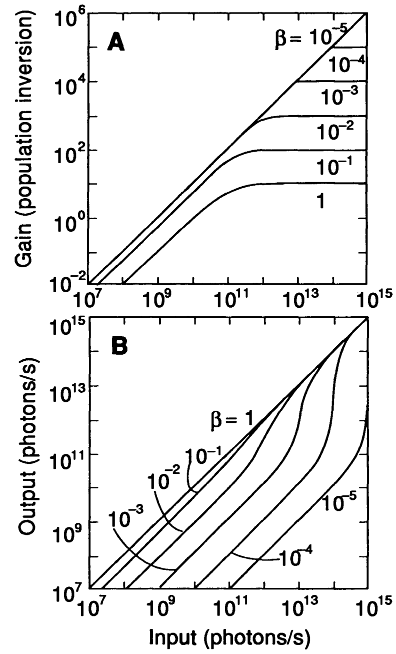

Fig. 5. Calculated gain (**A**) and light output (**B**) versus input power for microcavities on logarithmic scales. β is the fraction of spontaneous emission coupled into the cavity mode. Other parameters used are those of a conventional diode laser with a four-level medium approximation. An enhancement of the spontaneous emission coupled into the cavity mode is also assumed. The threshold in the input-output curve becomes unclear with increasing β.

Although it may not be meaningful to distinguish between spontaneous and stimulated emissions when all of the photons are emitted into the single cavity mode, the two kinds of emission processes can still be distinguished if attention is paid to the laser gain behavior. With increasing input power, the gain increases linearly within the region in which spontaneous emission dominates, whereas it is clamped at the threshold level in the laser oscillation region. Thus, in that sense, a fuzzy threshold still exists although it does not appear in the input-output curves even for $\beta = 1$. Even with this conventional definition of laser oscillation, however, an increase in β can decrease the threshold if other parameters are kept unchanged. Thus, β also indicates the material-photon coupling strength for stimulated emission. This result is consistent with the picture that the confinement of a photon in a smaller volume would give a larger β accompanied by a stronger electromagnetic field.

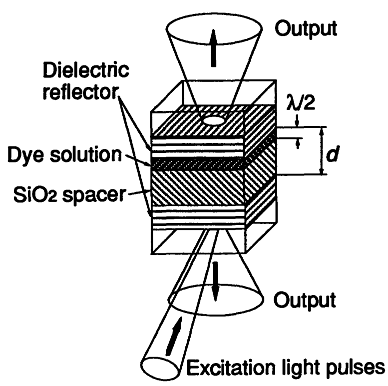

Fig. 6. Schematic of a planar microcavity structure containing a dye solution.

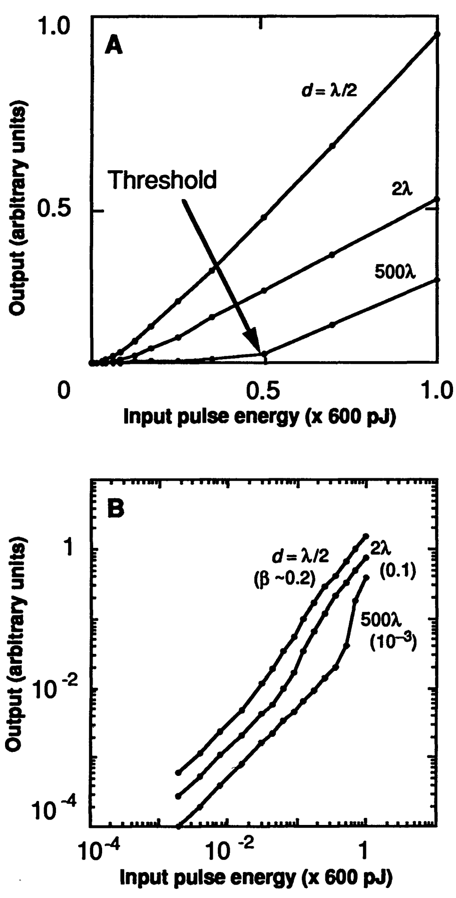

Fig. 7. Light output versus absorbed excitation laser pulse energy for two different microcavities and for a rather long cavity: (**A**) linear plots and (**B**) logarithmic plots. In both (A) and (B) the cavity-axis resonance wavelength was 560 nm. The thresholds of the microcavities are quite fuzzy, while that of the long cavity is clear. This result shows the nearly thresholdless laser operation of the planar microcavity.

The principle behind the thresholdless laser is different from that of the "one-atom maser" (6), in which the gain provided by a single-atom population inversion overcomes an extremely low cavity loss. Furthermore, the spontaneous emission power of an excited atom is not important in the microwave region, although it may be significant in the optical region because the spontaneous emission power increases with $1/\lambda^4$. Thus, the efficient use of spontaneous emission is also important for reducing power consumption in a laser.

A word should be said about the requirements for the laser medium. A large nonradiative transition process would disturb the thresholdless laser action even at $\beta = 1$ because only decay through stimulated emission provides efficient light emission. Therefore, it is also important to use a high-quantum-efficiency light-emitting material to achieve thresholdless laser operation.

With respect to the cavity geometry for thresholdless laser operation, a closed microcavity structure is the ideal one in which to completely confine the spontaneous emission into a single cavity mode (*16*). However, a large coupling of spontaneous emission into the laser mode can also be expected with a planar microcavity because the spontaneous emission concentrates around the cavity axis (Fig. 1).

Nearly Thresholdless Laser Oscillation of a Planar Microcavity Laser

Experimental observation of nearly thresholdless laser oscillation has been reported in which microcavities containing dye solutions are used instead of ultrathin semiconductors. This result may be attributed to the extremely high quantum efficiencies of laser dye solutions. The microcavity structure used in a recent experiment (*21*) is shown schematically in Fig. 6. In order to precisely control the thickness of dye solution, Ti films having 200-nm thicknesses were deposited on parts of one of the dielectric mirrors to act as a spacer for the introduction of a rhodamine 6G dye solution. An SiO_2 film having a thickness of an integer multiple of the half-wavelength was also deposited on the remaining mirror to change the cavity length while keeping the thickness of the dye solution constant. The space made by the Ti film was filled by

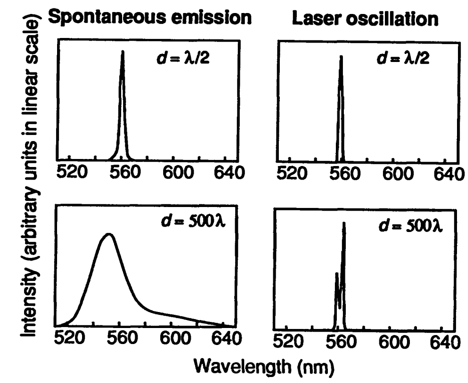

Fig. 8. Spontaneous and stimulated emission spectra of the λ/2 microcavity and the 500λ cavity.

capillary action with the dye solution. The dye solution was optically excited by a pulsed laser.

Figure 7 shows (A) linear and (B) logarithmic plots of output versus input for microcavities having two different mirror distances ($d = \lambda/2$ means no SiO_2 spacer). In these microcavities, the cavity-axis resonance wavelength was chosen to be 560 nm. For comparison, the curve for a cavity with large mirror separation (500λ cavity length) is also shown. As Fig. 1 reveals, this "long" cavity laser has a clear threshold feature. The coupling fraction β of spontaneous emission was evaluated to be $\sim 10^{-3}$. However, the thresholds of the microcavities are fuzzy, indicating nearly thresholdless laser action, demonstrating that the fractions of spontaneous emission coupled into the laser mode are very large. β was evaluated to be ~0.2 for the $d = \lambda/2$ cavity and ~0.1 for the 2λ cavity. These values are fairly large if we consider the very broadband emission spectrum of the dye solution.

There are no drastic changes between spontaneous and laser emission spectra for a microcavity laser, although narrowing is evident at the foot of the peaks when stimulated emission is dominant (Fig. 8). This result is due to the fact that even spontaneous emission is restricted by the single cavity resonance curve. There is a clear contrast between emission spectra of the microcavity and those of the "long" cavity laser, which show a conventional drastic narrowing above the threshold.

Although thresholdless laser operation has not yet been reported from a semiconductor device, the above properties of dye microcavities could be also expected in appropriately designed semiconductor microcavities. Since the first success in continuous operation of the current-injection VCSEL (*30*), marked progress has been made in constructing high-performance VCSELs (*31–33*). Further technological progress in these VCSELs can be combined naturally with cavity QED techniques and may lead to laser devices with thresholdless ultralow power consumption in the near future.

Prospects

The microcavity laser offers another attractive feature beside thresholdless laser operation: response speed in excess of 100 gigabitts per second (Gbps). One reason for this is the extremely short photon lifetime of an appropriately designed microcavity that comes from the extremely short cavity length. Another reason is the cavity-enhanced spontaneous emission rate. The response speed is increased by the square root of both factors. In a planar microcavity, although the increase in the spontaneous emission rate is at most a factor of ~ 2, the photon lifetime is reduced to $\sim 1/10$ of that of a conventional diode laser. Already, a response speed of over 50 Gbps has been demonstrated with a planar microcavity laser (*34*), a speed that cannot be achieved in lasers of conventional size. A three dimensionally or two dimensionally confined microcavity could further increase the response speed through larger increases in the spontaneous emission rate. Also related to multidimensional optical confinement is the "photonic bandgap" concept (*17, 35*), which may provide equivalent three-dimensional microcavities.

Also worth noting with microcavity optical devices are the photon statistics of the light output. There is a possibility of generating number-state light (*36*) from a microcavity semiconductor diode laser with a very low excitation power (*15*). This and other exciting possibilities remain to be more fully explored.

The application of cavity QED concepts to optical devices has just begun. There is hope that this effort will lead beyond conventional lasers to even more novel light sources.

REFERENCES AND NOTES

1. A. Einstein, *Z. Phys.* **18**, 121 (1917).
2. T. H. Maiman, *Nature* **187**, 493 (1960).
3. S. Haroche and D. Kleppner, *Phys. Today* **42**, 24 (January 1988).
4. A. G. Vaidyanathan, W. P. Spencer, D. Kleppner, *Phys. Rev. Lett.* **47**, 1592 (1981).
5. P. Goy, J. M. Raimond, M. Gross, S. Haroche, *ibid.* **50**, 1903 (1983).
6. D. Meschede, H. Walther, G. Müller, *ibid.* **54**, 551 (1985).
7. G. Rempe and H. Walther, *ibid.* **58**, 353 (1987).
8. W. Jhe *et al.*, *ibid.*, p. 666.
9. D. J. Heinzen, J. J. Childs, J. E. Thomas, M. S. Feld, *ibid.*, p. 1320.
10. D. J. Heinzen and M. S. Feld, *ibid.* **59**, 2623 (1987).
11. F. DeMartini, G. Innocenti, G. R. Jacobovitz, P. Mataloni, *ibid.*, p. 2995.
12. M. Suzuki, H. Yokoyama, S. D. Brorson, E. P. Ippen, *Appl. Phys. Lett.* **58**, 998 (1991).
13. E. Yablonovitch, T. J. Gmitter, R. Bhat, *Phys. Rev. Lett.* **61**, 2546 (1988).
14. H. Yokoyama, K. Nishi, T. Anan, H. Yamada, technical digest of the Topical Meeting on Quantum Wells for Optics and Optoelectronics, Salt Lake City, UT, March 1989, paper MD4; H. Yokoyama *et al.*, *Appl. Phys. Lett.* **57**, 2814 (1990).
15. Y. Yamamoto, S. Machida, K. Igeta, Y. Horikoshi, paper presented at the 6th Rochester Conference on Coherence and Quantum Optics, Rochester, NY, June 1989; *Opt. Commun.* **80**, 337 (1991).
16. T. Kobayashi, T. Segawa, A. Morimoto, T. Sueta, paper presented at the 43rd fall meeting of the Japanese Society of Applied Physics, Tokyo, September 1982; T. Kobayashi, A. Morimoto, T. Sueta, paper presented at the 46th fall meeting of the Japanese Society of Applied Physics, Tokyo, October 1985 (both in Japanese).
17. E. Yablonovitch, *Phys. Rev. Lett.* **58**, 2059 (1987).
18. H. Yokoyama and S. D. Brorson, *J. Appl. Phys.* **66**, 4801 (1989).
19. S. D. Brorson, H. Yokoyama, E. P. Ippen, *IEEE J. Quantum Electron.* **26**, 1492 (1990).
20. F. DeMartini and J. R. Jacobovitz, *Phys. Rev. Lett.* **60**, 1711 (1988).
21. H. Yokoyama, M. Suzuki, Y. Nambu, *Appl. Phys. Lett.* **58**, 2598 (1991).
22. P. W. Milonni and P. L. Knight, *Opt. Commun.* **9**, 119 (1973).
23. P. Stehle, *Phys. Rev. A* **2**, 102 (1970).
24. M. R. Philopott, *Chem. Phys. Lett.* **19**, 435 (1973).
25. G. Björk, S. Machida, Y. Yamamoto, K. Igeta, *Phys. Rev. A* **44**, 669 (1991).
26. T. Baba, T. Hamano, F. Koyama, K. Iga, *IEEE J. Quantum Electron.* **27**, 1347 (1991).
27. H. M. Tzeng, K. F. Wall, M. B. Long, R. K. Chang, *Opt. Lett.* **9**, 499 (1984).
28. A. J. Canpillo, J. D. Eversole, H.-B. Lin, *Phys. Rev. Lett.* **67**, 437 (1991).
29. K. H. Drexhage, in *Progress in Optics*, E. Wolf, Ed. (North-Holland, Amsterdam, 1974), vol. 12, p. 165.
30. F. Koyama, S. Kinoshita, K. Iga, *Trans. Inst. Elec. Comput. Eng. Jpn.* **E71**, 1089 (1988).
31. J. L. Jewell *et al.*, *Appl. Phys. Lett.* **54**, 1400 (1989).
32. A. Schere, J. L. Jewell, Y. H. Lee, J. P. Harbison, L. T. Florez, *ibid.* **55**, 2724 (1989).
33. R. S. Geels and L. A. Coldren, *ibid.* **57**, 1605 (1990).
34. Y. Nambu and H. Yokoyama, paper presented at the Quantum Electronics and Laser Science Conference, Baltimore, MD, May 1991.
35. S. John, *Phys. Today* **45**, 32 (May 1991).
36. One of the quantum mechanical states of light that satisfies the minimum uncertainty. The amplitude fluctuation of light is suppressed while the phase fluctuation is enhanced.

37. I thank S. D. Brorson, E. P. Ippen, Y. Nambu, M. Suzuki, K. Nishi, T. Anan, and H. Yamada for collaboration and helpful discussions.

Biomass and Carbon Budget of European Forests, 1971 to 1990

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In severely polluted areas, such as locally in Montshegorsk in northwestern Russia, all trees have died. However, measurements from Austria, Finland, France, Germany, Sweden, and Switzerland show a general increase of forest resources. The fertilization effects of pollutants override the adverse effects at least for the time being. Biomass was built up in the 1970s and 1980s in European forests. If there has been similar development in other continents, biomass accumulation in nontropical forests can account for a large proportion of the estimated mismatch between sinks and sources of atmospheric carbon dioxide.

Forests involve a larger variety of economic, cultural, and social dimensions than perhaps any other natural resource. Forests can be used for industrial and energy production purposes. In addition, they are part of the landscape accessible to people. Forest-dependent fauna and flora represent an enormous heritage of biodiversity. Forests, in comparison to, say, oil reserves, are widely distributed among countries, different regions, owners, and owner groups. Non-owners enjoy environmental benefits from forests and affect management practices by means of publicity and the democratic process. These special characteristics of forests have stimulated discussion and debate on the resource. The discussion in Europe in the 1980s largely focused on one issue, that of the impact of air pollutants on forests.

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Air pollutants affect forest ecosystems in many ways. Surveys in Finland, for instance, revealed a decline of epiphytic lichen species over an area of more than 100,000 km^2 during the past 25 years (*1*). Trees themselves can rely on nutrition from deeper soil layers and are less susceptible than the sensitive lichen species to air pollution damage but, as seen in severe cases of decline, trees have their tolerance limits.

Research programs in both North America and Europe have addressed the impacts of air pollutants on ecosystems (*2*), and forest surveys and growth investigations have been carried out for a long time. Results from all the different studies form an important basis for judgments about the past and future development of forest resources. We analyze and discuss various research results, realizing that any statistical presentation is bound to oversimplify and distort the extreme diversity of what is called "European forest" (*3*). We focus on the growing stock and growth