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GaAs/AlAs coupled multilayer cavity structures for terahertz emission devices

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GaAs/AlAs coupled multilayer cavity structures are proposed as terahertz emission devices. Two cavity modes with an optical frequency difference in the terahertz region can be realized when two cavity layers are coupled by an intermediate distributed Bragg reflector multilayer. Interference between the enhanced light fields of the cavity modes has been demonstrated by the simultaneous injection of two cavity-mode lights using an ultrashort pulse laser. Such coupled multilayer cavity structures are promising for use as compact and room temperature operable terahertz emission devices based on difference frequency generation by the cavity-mode lights. © *2009 American Institute of Physics*. [doi:10.1063/1.3226667]

Terahertz emitters based on semiconductor devices have been widely investigated because of the wide range of possible applications such as wireless communications, spectroscopy, and imaging. Many kinds of devices such as resonant tunneling diodes,[1] photomixers,[2,3] and *p*-type Ge lasers[4] have been developed as coherent terahertz-wave sources. Although remarkable progress on terahertz quantum cascade lasers[5–7] has been made in recent years, near room temperature operation has not been demonstrated yet. Difference frequency generation (DFG) in III-V semiconductors is an attractive method of terahertz-wave generation because of the large second-order nonlinearity. Efficient terahertz generation based on DFG has previously been demonstrated using a GaP crystal excited by two individual lasers.[8–10]

Optical microcavities are good candidates for nonlinear optical devices because an extremely strong light field is realized in the cavity layer. Recently, we have demonstrated all-optical Kerr gate switches based on GaAs/AlAs multilayer cavity structures.[11,12] The nonlinear phase shift induced by pump light is drastically enhanced in the half-wavelength ($\lambda/2$) cavity layer sandwiched between two GaAs/AlAs distributed Bragg reflector (DBR) multilayers. Efficient wavelength conversion using the second-order optical nonlinearity is also possible in a mulitilayer cavity structure grown on a non-(001) substrate.[13] In fact, Kaneko *et al.*[14] demonstrated blue vertical-cavity surface emitting lasers (VCSELs) based on second-harmonic generation (SHG) grown on (113)B GaAs substrates. In this paper, GaAs/AlAs coupled multilayer cavity structures are proposed for terahertz emission devices. We have demonstrated that two cavity modes are realized in the coupled cavity structure and observed interference between the enhanced light fields of the two cavity modes. These characteristics are promising for terahertz-wave generation based on DFG.

An example of the GaAs/AlAs coupled multilayer cavity structure proposed in this paper is shown in Fig. 1. Two $\lambda/2$ cavity layers are coupled by an intermediate GaAs/AlAs DBR multilayer, and the 13-period DBR multilayers are formed at both sides of the coupled cavity structure. The coupling strength is strongly related to the number (N_c) of multilayer periods in the intermediate DBR, and also controlled by the refractive index contrast between the materials in the DBR multilayer. Figure 2 shows transmission spectra of the coupled cavity structure simulated through the conventional transfer matrix method. In the simulation, each DBR multilayer was assumed to consist of 111-nm-thick GaAs and 130-nm-thick AlAs layers, and a 222-nm-thick GaAs layer was used as each of the two $\lambda/2$ cavity layers. Linear refractive indices of 3.38 and 2.89 were used for the GaAs and AlAs layers, respectively, and the number of multilayer periods in the intermediate DBR was varied from $N_c=6.5$ to 14.5. In each spectrum in Fig. 2, two cavity modes with different resonant wavelengths around 1500 nm are clearly seen in the center of the high reflection band. This means that a degenerate cavity mode is split into two different modes by the coupling of the $\lambda/2$ cavity layers using the intermediate DBR. A smaller number of multilayer periods in the intermediate DBR leads to a larger wavelength splitting of the cavity modes. This behavior closely resembles the energy level splitting of bonding and antibonding states in a coupled quantum well structure. Since the two equivalent cavities are coupled by the intermediate DBR, two cavity modes only approach each other when the coupling strength is weakened by increasing N_c. Note that the optical frequency difference between the two cavity modes can be precisely defined in the terahertz region by the number of multilayer periods in the intermediate DBR (6.36, 3.27, and 1.72 THz for $N_c=6.5$, 10.5, and 14.5, respectively).

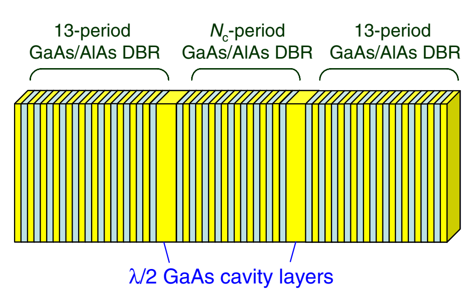

FIG. 1. (Color online) An example of the GaAs/AlAs coupled multilayer cavity structure proposed in this paper. Two cavity layers are coupled by the N_c-period intermediate DBR.

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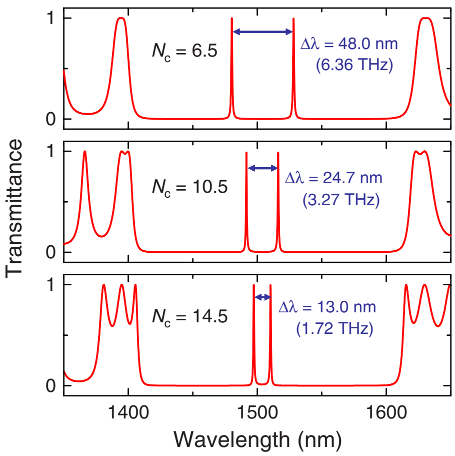

FIG. 2. (Color online) Transmission spectra of the GaAs/AlAs coupled multilayer cavities with N_c=6.5, 10.5, and 14.5.

Figure 3 shows spatial distributions of the internal light intensities of the two cavity modes (λ=1491.6 and 1516.2 nm) in the GaAs/AlAs coupled multilayer cavity with N_c =10.5. The internal light intensity of each cavity mode is strongly enhanced in both cavity layers. Therefore, strong nonlinear optical responses are expected at 1491.6 and 1516.2 nm. In Fig. 3, ten light intensity peaks can be seen in the intermediate DBR region when λ=1491.6 nm, while there are nine intensity peaks for λ=1516.2 nm. This indicates that the optical phase difference between the two cavity modes must be exactly 180° at the left-side (right-side) cavity layer when the two phases are aligned at the right-side (left-side) cavity layer.

We also simulated propagation of two cavity-mode lights, which were simultaneously injected by an ultrashort laser pulse, in the GaAs/AlAs coupled multilayer cavity with N_c=10.5. A one-dimensional finite difference time domain method was used for the time-dependent simulation on the internal light intensity distribution. The incident light source used in the simulation was a single 100 fs Gaussian pulse, which had a spectral width of 33.3 nm, wider than the wavelength difference (Δλ=24.7 nm) between the two cavity modes. The center wavelength of the Gaussian pulse was set

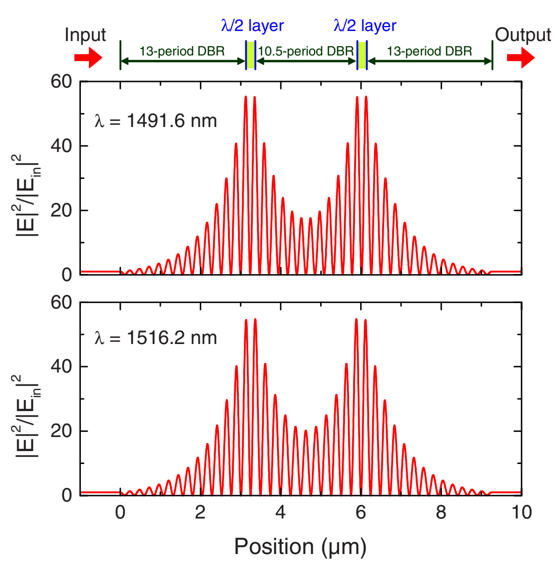

FIG. 3. (Color online) Spatial distributions of the internal light intensities of two cavity modes (λ=1491.6 and 1516.2 nm) in the GaAs/AlAs coupled multilayer cavity with N_c=10.5.

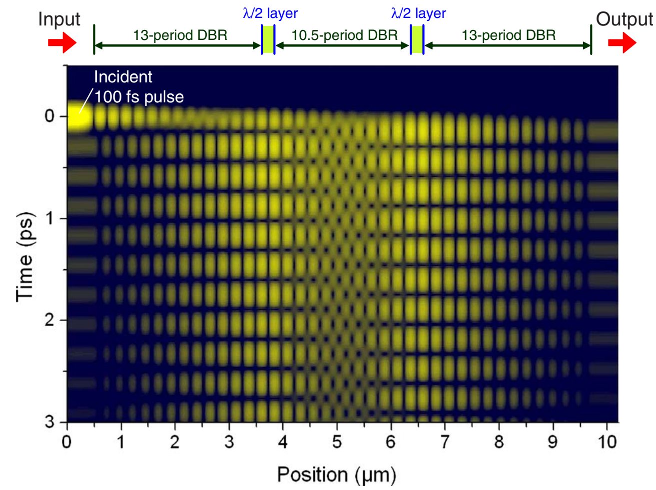

FIG. 4. (Color online) A mapping of the time-dependent light intensity in the GaAs/AlAs coupled multilayer cavity with N_c=10.5 after two cavity-mode lights were simultaneously injected by a single 100 fs Gaussian pulse from the left side. The light intensity is plotted in log scale.

at the midpoint of the two cavity modes. Figure 4 shows a mapping of the time-dependent light intensity distribution after a 100 fs Gaussian pulse was incident from the left side, where light intensity is plotted in log scale. The intensity of the injected light into the coupled cavity structure oscillates between the two cavity-layer regions as a function of time, and its amplitude decays through light emission to the outside. The oscillation frequency is very consistent with the optical frequency difference between the two cavity modes, indicating that the time-dependent oscillation observed in Fig. 4 results from interference between the enhanced light fields of the cavity modes. The light intensity transmitted through the coupled cavity structure (the right-side region in Fig. 4) also shows the oscillating decay as a function of time.

In order to examine the interference behavior of two cavity-mode lights, a GaAs/AlAs coupled multilayer cavity structure (Fig. 1) with N_c=10.5 was grown on a (001) GaAs substrate by molecular beam epitaxy. The optical transmission properties were measured after removing the substrate[15] because optical reflection at the substrate-side surface would affect transmission characteristics of the sample. Intrinsic characteristics of two cavity modes are not influenced by removing the substrate. 100 fs laser pulses with a 100 kHz repetition rate were used as light sources for the simultaneous injection of two cavity-mode lights. All optical measurements were performed at room temperature. Figure 5(a) shows the measured spectrum of the laser pulses transmitted through the coupled cavity sample. The center wavelength of the incident laser pulses was tuned to 1543 nm. Transmission peaks corresponding to the two cavity modes were clearly observed at 1525.5 and 1556.7 nm, indicating that two cavity-mode lights were simultaneously injected. The observed cavity-mode wavelengths were slightly different from the simulated results (λ=1491.5 and 1516.2 nm) because of the slight difference (∼2%) in the layer thickness between the actual and designed structures. The quality factors deduced from the spectral linewidths were 450 and 400 for the cavity modes with λ=1525.5 and 1556.7 nm, respectively. The quality factor should be further improved by increasing multilayer periods of the top and bottom DBRs with keeping almost the same frequency difference, which was confirmed by the simulated results using transfer matrix method. The

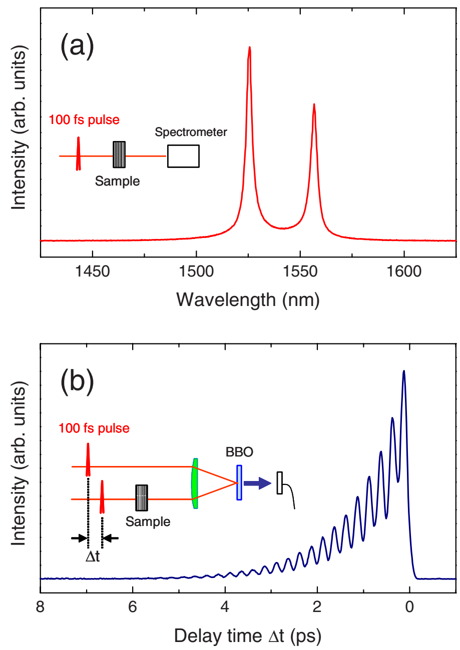

FIG. 5. (Color online) (a) Measured spectrum of the 100 fs laser pulses ($\lambda_{center}=1543$ nm) transmitted through the GaAs/AlAs coupled multilayer cavity with $N_c=10.5$ grown on the (001) GaAs substrate. (b) Time-resolved cross-correlation measurement between the 100 fs laser pulses with and without transmission path through the coupled cavity sample.

temporal profile of the transmitted pulse was studied by time-resolved cross-correlation measurements between the 100 fs pulses with and without a transmission path through the coupled cavity sample.[16] A nonlinear optical crystal of beta barium borate was used to detect the cross-correlation signal. Figure 5(b) shows the cross-correlation signal plotted as a function of delay time. The oscillating decay caused by the interference of the two cavity-mode lights is clearly observed. The oscillation frequency determined from Fig. 5(b) was 4.0 THz, which was almost the same as the optical frequency difference (3.9 THz) shown in Fig. 5(a).

A large overlap between the enhanced light fields of two cavity modes is extremely effective for optical frequency mixing. When two cavity modes are simultaneously excited, such overlap can occur owing to the interference of the two fundamental cavity-mode lights as shown in Fig. 4. Growth of the coupled cavity structure on a non-(001) GaAs substrate is essential for frequency mixing because the effective second-order nonlinear coefficient is zero on (001) oriented substrates due to crystal symmetry.[13] In our recent study, strong sum frequency generation (SFG) was observed in a (113)*B* GaAs/AlAs coupled multilayer cavity with $N_c=10.5$ when the two cavity modes were simultaneously excited by 100 fs laser pulses.[17] The peak intensity of the SFG signal was more than 400 times larger than that of the SHG signal from a (113)*B* GaAs substrate alone, indicating that the effective second-order nonlinearity was strongly enhanced by the cavity effect. Therefore, we can also expect strong terahertz-DFG using the two cavity modes of the GaAs/AlAs coupled multilayer cavity grown on the (113)*B* GaAs substrate. In the case of a bulk nonlinear crystal, phase matching between the fundamental and terahertz waves is strongly required for high conversion efficiency. However, the phase matching conditions are not important in the coupled cavity structure, since the generation region is markedly smaller than the terahertz wavelength. Note that two fundamental cavity-mode lights will be generated by current injection using a VCSEL-type structure. For example, two cavity layers containing gain materials with second-order nonlinearity are coupled by the intermediate *p*-type DBR and they are sandwiched between the top and bottom n-type DBRs. This kind of terahertz emission device based on the VCSEL-type structure would be simple and compact because terahertz-DFG is expected to be easily obtained by current injection at room temperature. Proposed terahertz emission devices will be fabricated using commercial GaAs-based VCSEL technologies. The epitaxal growth of III-V heteromaterials and device processing are quite similar to those of the commercial VCSELs, which are crucial advantages for the production of proposed devices.

In conclusion, we have proposed a terahertz emission device based on a GaAs/AlAs coupled multilayer cavity structure in which two cavity layers are coupled by the intermediate DBR. Two cavity modes are realized in the center of the high reflection band, and the frequency difference between these modes can be precisely defined in the terahertz region by the number of multilayer periods in the intermediate DBR. Light propagation in the coupled multilayer cavity has been studied when two cavity-mode lights are simultaneously injected by a 100 fs laser pulse. The simulation and experimental results reveal that strong frequency mixing can be expected owing to the interference between the enhanced light fields of the cavity modes. A VCSEL-type structure with such a coupled cavity has the potential to act as a simple and compact terahertz emission device operating at room temperature because efficient terahertz-DFG of the two cavity-mode lights is expected by current injection.

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