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# Four-Wave Mixing in a GaAs/AlAs Triple-Coupled Multilayer Cavity for Novel Ultrafast Wavelength Conversion Devices

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## Abstract
**Novel ultrafast wavelength conversion devices based on a GaAs/AlAs triple-coupled multilayer cavity are proposed. A clear wavelength-converted signal with an ultrafast response was demonstrated by four-wave mixing using three cavity modes realized in the triple-coupled cavity.**

## 1. Introduction
Optical nonlinear phenomena in a semiconductor vertical microcavity are very interesting and useful to construct novel all-optical devices for dense parallel processing. We have demonstrated optical Kerr gate switches based on a GaAs/AlAs multilayer cavity with InAs quantum dots (QDs) embedded in strain-relaxed barriers [1,2]. The strong internal light electric field due to the cavity effects yields drastic enhancement of nonlinear phase shift in the half-wavelength ($\lambda/2$) cavity layer containing QDs, which results in strongly enhanced optical Kerr signal. A coupled cavity system has a unique feature of multiple cavity modes providing new functionality. In our recent studies, terahertz wave generation has been demonstrated by difference frequency generation of two cavity modes realized in a GaAs/AlAs coupled multilayer cavity grown on a (113)B GaAs substrate [3]. In this paper, a GaAs/AlAs triple-coupled multilayer cavity is proposed for novel ultrafast wavelength conversion devices operating in the telecommunication wavelength range. The wavelength conversion is based on four-wave mixing (FWM) using three cavity modes realized in the triple-coupled cavity. Time-resolved FWM measurements were performed using femtosecond laser pulses with the modified spectral shape to demonstrate the wavelength conversion.

## 2. GaAs/AlAs triple-coupled multilayer cavity
The triple-coupled cavity structure consists of three $\lambda/2$ cavity layers and four distribute Bragg reflector (DBR) multilayers as shown in Fig. 1(a). The series connection of three cavity layers yields three cavity modes with optical frequencies of $\omega_1$, $\omega_2$ and $\omega_3$ in the center of the high-reflection band. Due to the symmetric structure, the frequency separations between two adjacent modes are the same as each other, that is, $\omega_1 - \omega_2 = \omega_2 - \omega_3$. Let us consider FWM processes when the mode lights with frequencies of $\omega_1$ and $\omega_2$ are simultaneously injected. As well as the degenerate FWM signal with each frequency, the FWM signal with $2\omega_2 - \omega_1$ should be efficiently generated because the frequency is coincident with the other mode frequency of $\omega_3$. Since each mode has a strong internal electric field, the remarkable enhancement of the FWM signal is expected. According to this FWM process, the input light frequency of $\omega_1$ could be quickly converted to the output frequency of $\omega_3$ by the irradiation of the control light with $\omega_2$. The response time should be extremely short and limited by the photon lifetime of the triple-coupled cavity.

The sample structure shown in Fig. 1(a) was grown on a (001) GaAs substrate by molecular beam epitaxy (MBE). Two 10.5-period GaAs/AlAs (111 nm/130 nm) DBRs were used for the series connection of three $\lambda/2$ cavity layers (222-nm-thick GaAs), and 13-period DBRs were formed at both sides. Before optical measurements, the GaAs substrate was completely removed by mechanical polishing and selective wet etching. Figure 1(b) show the measured optical transmission spectrum. Transmission peaks corresponding to the three cavity modes were clearly observed at 1466.6, 1485.3 and 1502.2 nm.

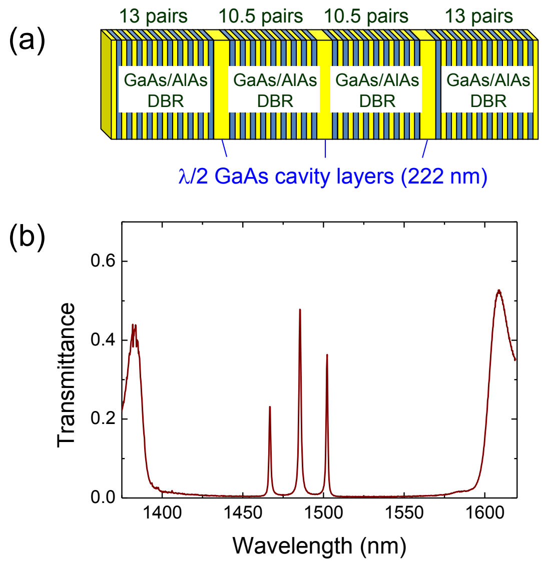


Fig. 1 (a) Structure of the GaAs/AlAs triple-coupled multilayer cavity. (b) Measured optical transmission spectrum.

## 3. Time-resolved FWM measurements
Time-resolved FWM measurements were performed at room temperature using a femtosecond laser system with a 100 kHz repetition rate. The incident laser pulses were

spectrally shaped to cover only the two mode frequencies on the short wavelength side as shown in Fig. 3(a), which was performed by the spectral width restriction using a slit between a pair of gratings and cylindrical lenses [4]. Then, the laser pulses were divided into $k_a$ and $k_b$ pulses by a beam splitter and both pulse beams were focused on an area of about 140 μm diameter of the sample surface. Incident powers of the $k_a$ and $k_b$ pulses were 2 and 10 mW, respectively. A relative delay time ($\Delta t$) of the $k_b$ pulse was varied using a mechanical delay stage. The $k_a$ beam was chopped at 400 Hz for the standard lock-in detection. In order to detect only the FWM signal ($2k_b$ - $k_a$) which was spatially separated from the $k_a$ and $k_b$ pulses [5], a small aperture with a diameter of about 3 mm was placed between the collimating lens and cooled InGaAs photodiode (PD) detector (see an inset of Fig. 2). The spectrum was also measured using a spectrometer with a cooled InGaAs PD array.

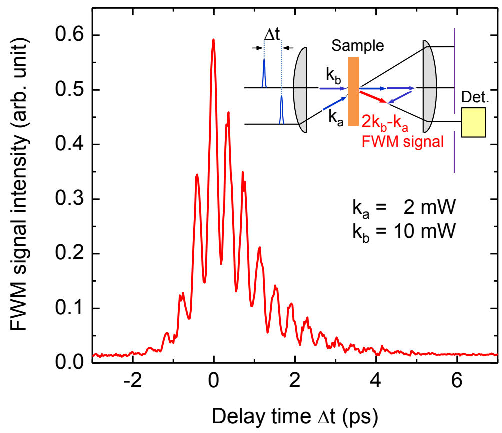


Fig. 2 Temporal profile of FWM signal measured using laser pulses with the spectral shape of Fig. 3(a).

Figure 2 shows the $\Delta t$ dependent FWM signal measured using spectrally-shaped laser pulses. The oscillation decay was clearly observed because of the interference between the FWM signals with different frequencies related to the three cavity modes. The decay constant was about 1 ps, indicating the ultrafast FWM response.

Figures 3(a) and 3(b) show spectra of the incident pulses and FWM signal at $\Delta t = 0$, respectively. Although incident pulses covered only the two modes of $\omega_1$ and $\omega_2$ as shown in Fig. 3(a), we clearly observed a FWM signal whose frequency was outside of the incident pulses, in addition to the degenerate FWM signals of the two cavity modes with frequencies of $\omega_1$ and $\omega_2$. This indicates that the frequency conversion was successfully realized using three cavity modes of the triple-coupled cavity. The peak frequency of the additional FWM signal corresponds to that ($\omega_3$) of the other mode, while the shoulder structure was significantly observed in the long wavelength side. The broken vertical line in Fig. 3(b) indicates the position of $2\omega_2$ - $\omega_1$ where the signal peak is expected for the wavelength conversion through the FWM process. In this sample, $2\omega_2$ - $\omega_1$ was not exactly coincident with $\omega_3$ because of the layer-to-layer thickness variation caused by slight and gradual changes of Ga and Al fluxes during MBE of the multilayer structure. This is the reason why the wavelength-converted signal showed smaller intensity with the shoulder structure compared with the degenerate FWM signals. Significant improvements in the wavelength conversion would be expected by the precise control of each layer thickness in the triple-coupled multilayer cavity structure and introducing good nonlinear materials such as InAs quantum dots in the λ/2 cavity layers.

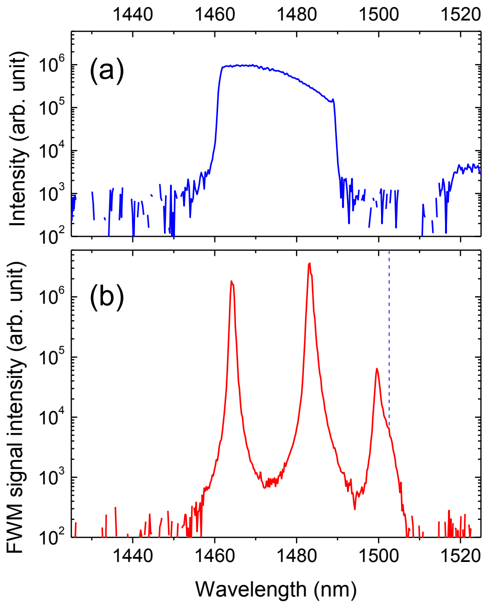


Fig. 3 Spectra of (a) incident laser pulses and (b) FWM signal at $\Delta t = 0$.

## 4. Conclusions

We have proposed novel ultrafast wavelength conversion devices based on nonlinear FWM process using three cavity modes with optical frequencies of $\omega_1$, $\omega_2$ and $\omega_3$, which are realized in a GaAs/AlAs triple-coupled multilayer cavity. The wavelength conversion was successfully demonstrated by the FWM signal observation with the mode frequency of $\omega_3$ when the triple-coupled cavity sample was excited by spectrally-shaped laser pulses covering only the two mode frequencies of $\omega_1$ and $\omega_2$. The proposed planar-type devices would be useful for future optical processing system.

## References

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