Normally On Reflection-Type Two-Wavelength Quantum-Well Modulator with Balanced Cavity Design

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***Abstract*— We have demonstrated a reflection-type two-wavelength modulator with a novel balanced cavity design. Simultaneous operations at wavelengths of around 860 and 896 nm have been achieved. By using such a new cavity design similar operating voltages have been obtained for both wavelengths. Under separate biasing voltages of 14.5 and 11 V on each quantum-well absorbing region, the maximum reflectivity changes were around 50%.**

***Index Terms*—Fabry–Perot resonators, optical switches, quantum confined Stark effect, quantum-well devices, wavelength-division multiplexing.**

SURFACE-NORMAL quantum-well modulators based on quantum-confined Stark effect (QCSE) are potentially useful for applications such as optical communication [1], optical interconnects [2], and optical switching networks [3]. Because of their compatibility with other semiconductor devices and the surface normal configuration, they can also be easily integrated to form two-dimensional (2-D) arrays for optical computing and smart pixel applications [4]. Recently we have demonstrated a two-wavelength Fabry–Perot type quantum-well (QW) modulator [5]. The two-wavelength operation opens the possibility for doubling the systems data throughput and increasing the flexibility of system designs. In this letter, an improved two-wavelength modulator is presented. The device is based on a balanced cavity design, which allows a simpler matching condition for the long-wavelength operation, and, therefore, a easier device growth procedure.

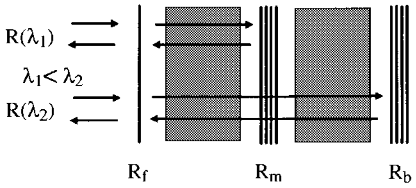

Fig. 1. Schematic of the two-wavelength modulator design.

The schematic for design of the two-wavelength modulators is shown in Fig. 1. As we can see from this figure, two QW absorbing regions with different operating wavelengths are put together into a single device. Quantum wells for the short wavelength are placed above those for the long wavelength to avoid unnecessary absorption of the short-wavelength photons. Besides, an additional middle reflector R_m is inserted in between the two absorbing regions. In our previous design in [5], a broad-band DBR mirror was used to serve as the middle reflector. For the long-wavelength light, this earlier design has to simultaneously satisfy the resonance condition in both of the front cavity and the rear cavity. Then, a stringent matching condition (in terms of layer thickness) is required and a big difference in operating voltages is difficult to avoid.

In this new design, the middle reflector is designed to serve as a reflector for the short-wavelength light while as a transmitting filter for the long-wavelength light. In this way, the effective front-mirror reflectivity for the long-wavelength light is simply that of the air-semiconductor interface, the same as that for the short-wavelength light. The upper half above the middle reflector serves as the resonant cavity for the short-wavelength light, while the whole structure serves as the cavity for the long-wavelength light. Because of the transparent property of middle reflector for the long-wavelength light, the front-mirror reflectivities are the same for both wavelengths. Besides, for the long-wavelength light, both the front and back cavities are linked together to become a single cavity without any coupling effect. It greatly simplifies the cavity matching conditions that are needed in the previous design. We can also easily design the cavities so that operating voltages for both wavelengths are similar.

To achieve a filter-type transmission characteristics for the middle reflector, we used a DBR stack with a $\lambda/4$ phase shift at the center (or two face-to-face DBR stacks). Due to its symmetric reflection property, this structure has a total transmission band at the center of the reflection band and the reflectivity increases with wavelengths away from the center wavelength. For a desired total transmission at a designed wavelength of 895 nm (the wavelength picked for long-wavelength operation), we used the $Al_{0.1}Ga_{0.9}As$–AlAs DBR with two face-to-face 7-pair stacks. The simulated reflection spectrum is shown in Fig. 2. A transmission band centered at 895 nm is obtained. On the other hand, high reflectivities over 85% can be obtained from 840 to 860 nm. These reflectivities are high enough to produce an excellent on-state performance for the short-wavelength modulator.

In real devices, we chose GaAs–AlGaAs and InGaAs–AlGaAs material systems to build our QW layers. The two

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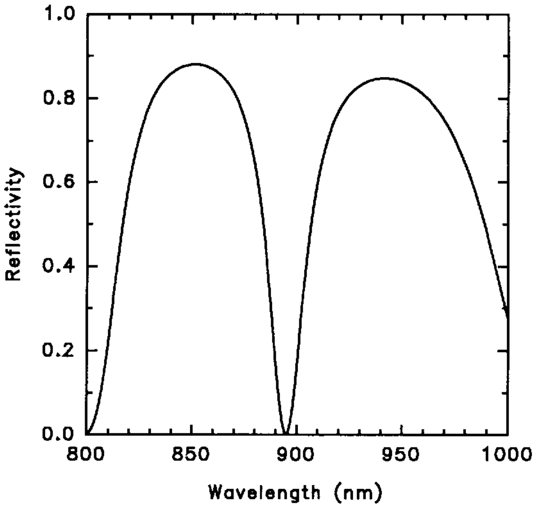
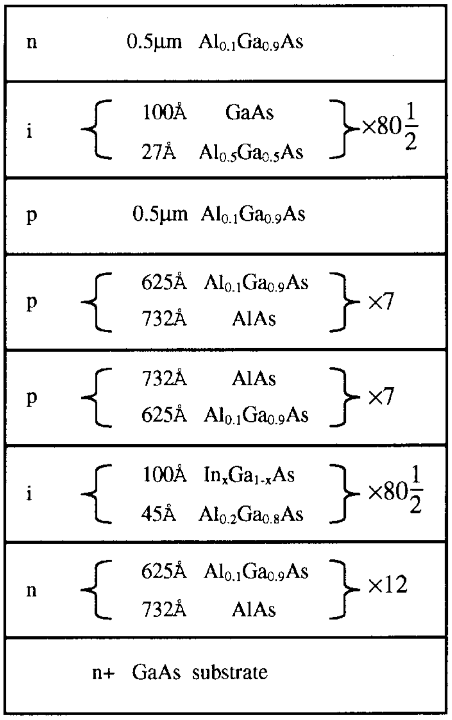
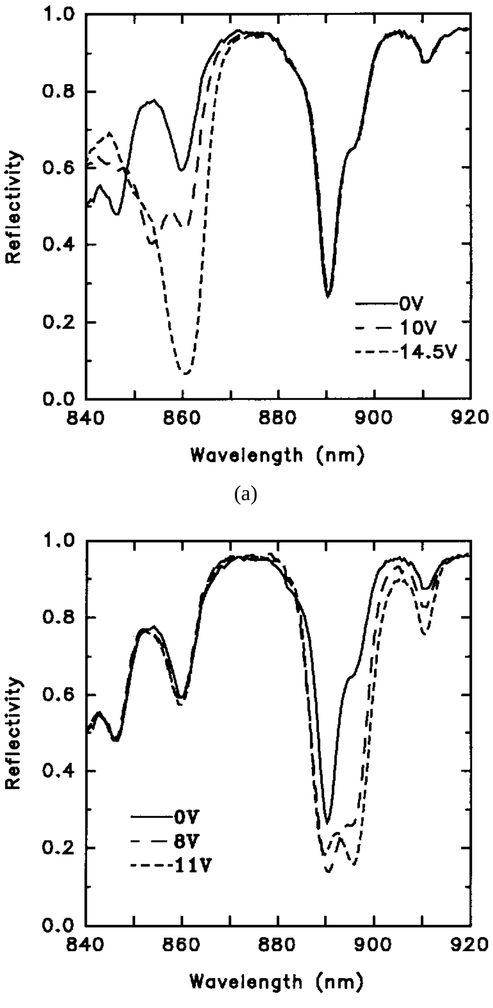


Fig. 2. Simulated reflection spectrum of the filter-type middle reflector, which consists of two face to face 7-pair $Al_{0.1}Ga_{0.9}As$–AlAs DBR stacks.



n	$0.5\mu m$ $Al_{0.1}Ga_{0.9}As$		
i	100Å GaAs 27Å $Al_{0.5}Ga_{0.5}As$	$\times 80\frac{1}{2}$
p	$0.5\mu m$ $Al_{0.1}Ga_{0.9}As$		
p	625Å $Al_{0.1}Ga_{0.9}As$ 732Å AlAs	$\times 7$
p	732Å AlAs 625Å $Al_{0.1}Ga_{0.9}As$	$\times 7$
i	100Å $In_xGa_{1-x}As$ 45Å $Al_{0.2}Ga_{0.8}As$	$\times 80\frac{1}{2}$
n	625Å $Al_{0.1}Ga_{0.9}As$ 732Å AlAs	$\times 12$
	n+ GaAs substrate		

Fig. 3. Complete layer structure of the new balanced cavity two-wavelength modulator.



(a)

(b)

Fig. 4. Reflection spectra of two-wavelength modulator under various biasing voltages (a) on the upper short-wavelength QW's and (b) on the lower long-wavelength QW's.

operating wavelengths were selected to be around 860 and 895 nm. The whole structure, grown by MBE, is shown in Fig. 3. We used the n-i-p-i-n back-to-back diode configuration so the two diodes for different wavelengths can be biased separately. The structure starts with 12 pairs of n-type $Al_{0.1}Ga_{0.9}As$ (625-Å) AlAs (732 Å) layers used as the bottom DBR mirror. 80 periods of undoped $In_xGa_{1-x}As$ (100-Å)–$Al_{0.2}Ga_{0.8}As$ (45-Å) QW's were grown next for the long-wavelength operation. Then the filter-type middle reflector, which consists of two face-to-face seven pairs p-type $Al_{0.1}Ga_{0.9}As$ (625-Å)–AlAs (732 Å) DBR stacks, was grown. After that, 80 periods of GaAs (100-Å)–$Al_{0.5}Ga_{0.5}As$ (27-Å) QW's were grown for the short-wavelength operation. Finally an n-type $Al_{0.1}Ga_{0.9}As$ contact layer was grown. The thickness of this layer was chosen so that resonances at 860 and 895 nm can be simultaneously obtained.

Device was then fabricated by two mesa-etching steps to separately define the ohmic contact for each electrode. Reflection spectra were measured with separate biasing voltages on each QW absorbing layer. The modulated spectra for the short-wavelength operation and the long-wavelength operation are respectively shown in Fig. 4(a) and (b). A clear two-wavelength operation is obtained. Each wavelength operated independently without any significant crosstalk. As we can see from Fig. 4, due to this new balanced cavity design, the two modulators can be turned off by similar biasing voltages of 14.5 and 11 V. Reflectivity changes of over 50% were achieved at both operating wavelengths.

In conclusion, we have successfully fabricated a novel balanced-cavity reflection-type normally-on two-wavelength modulator. Good modulation performance was observed at wavelengths of 860 and 895 nm. Due to the balanced cavity design, the turn-off voltages for the two wavelengths were similarly to be 14.5 and 11 V. Reflectivity changes obtained for both wavelengths were around 50%.

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