Long-wavelength multiple quantum well modulators

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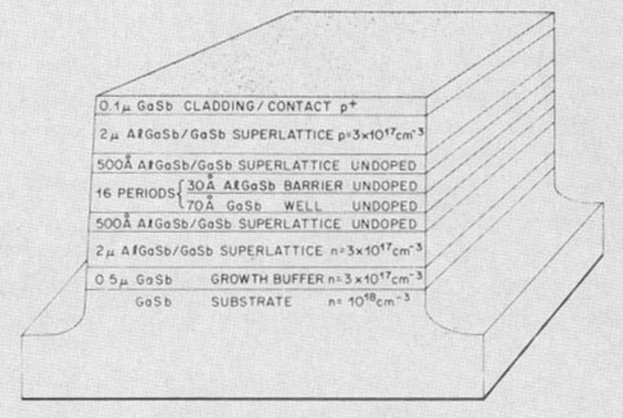
A variety of novel physical effects have been observed in multiple quantum wells (MQWs), which are thin layers of a low band-gap semiconductor surrounded by higher band gap material. Frequently, quantum mechanical effects are manifested in useful, macroscopic properties. Several years ago, it was discovered that large changes in the zero-point energies of particles in MQWs could be achieved by the application of an electric field perpendicular to the quantum well layers.[1] This leads to significant changes in the effective band-gap energy, which, in turn, leads to changes in the optical absorption coefficient for wavelengths near the band gap. Although a typical value of the change in absorption coefficient with electric field in bulk GaAs would be $\Delta\alpha = 140\ \text{cm}^{-1}$, in MQWs, $\Delta\alpha = 15000\ \text{cm}^{-1}$ has been observed.[1] This large $\Delta\alpha$ is obviously useful for making optical modulators and other optoelectronic devices.

A major limitation with this technology has been the wavelength of operation of these devices. Since virtually all work has been performed with GaAs wells and AlGaAs barriers, devices have operated near $\lambda = 0.85\ \mu\text{m}$, the band gap of GaAs. Although this wavelength is useful for some applications, the majority of optoelectronic systems have been migrating to $\lambda = 1.3$ or $1.5\ \mu\text{m}$, where the attenuation in optical fibers is roughly an order of magnitude lower and bandwidths are much higher. Extending the GaAs/AlGaAs MQW work to other materials which would have band-gaps near these wavelengths has been a major difficulty, because these devices require high quality growth. Typically, devices are made with a set of quantum wells ~100 Å wide. These wells need to have uniform thickness and smooth walls that are free from defects. In addition, the background doping in the wells must be on the order of $5 \times 10^{15}\ \text{cm}^{-3}$ or less, and the wells need to be surrounded with moderately heavily doped p and n contact layers. This can be achieved fairly routinely in GaAs/AlGaAs, because of the years of experience built up in molecular beam epitaxy (MBE) growth in this system, but longer-wavelength devices require similar quality growth in much more difficult material systems. A moderate $\Delta\alpha = 700\ \text{cm}^{-1}$ was observed at $\lambda = 1.53\ \mu\text{m}$ in GaInAs/AlInAs MQWs,[2] but larger effects were elusive.

The past year has seen much progress in two material systems for these long-wavelength devices. High quality MQWs were grown in InGaAs with InP barriers by metal-organic carrier vapor deposition (MO-CVD) and used to make a high speed modulator.[3] This device had a measured $\Delta\alpha = 3700\ \text{cm}^{-1}$ at $\lambda = 1.62\ \mu\text{m}$, and a bandwidth of 5.3 *GHz*. Another approach, which used GaSb wells with AlGaSb barriers, is shown in Fig. 1.[4] Here, a set of 16 GaSb quantum wells was grown via MBE in the center of an optical waveguide. This waveguide permits the interaction length between the light and the MQWs to be equal to the length of the device, which was 83 μm. The device, which had a $\Delta\alpha = 5500\ \text{cm}^{-1}$ at $\lambda = 1.55\ \mu\text{m}$, demonstrated an 11:1 on/off ratio and a bandwidth of 3.7 *GHz*.

Although it is clear that improvements in the quality of epitaxial growth was critical to these results, many unanswered questions remain. In the InGaAs system, the well material is a ternary, rather than a binary semiconductor, and the effect of alloy fluctuations on the effects is still to be investigated in detail. The details of the band structure and selection rules in the GaSb/AlGaSb system is still under investigation, with an eye toward reducing the insertion loss of the modulator, which is currently 12 dB. But this recent progress has fueled hopes that improvements in advanced semiconductor growth techniques will make the novel quantum physical effects observed at $\lambda = 0.85\ \mu\text{m}$ and the devices based on them available at longer wavelengths.



Schematic view of GaSb/AlGaSb multiple quantum well electroabsorptive modulator. A set of 16 quantum wells, each 70Å thick, was placed in the center of an optical waveguide. The length of the device was only 83 μm. Due to the high quality growth of the quantum wells, a large electroabsorption effect was seen. The modulator had an on/off ratio of 11:1 and a bandwidth of 3.7 GHz at a wavelength of 1.55 μm.

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Nonlinear optical lightwave local network

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Nonlinear effects in fibers have been primarily seen as a limitation to lightwave system performance. A recently demonstrated[1] network instead turns nonlinear optics to advantage by using stimulated Brillouin scattering to provide channel selection in a densely packed wavelength division multiplexed network.

In wavelength multiplexed lightwave local networks, where many users' signals are combined on a single fiber, the central problem is channel selection: how a user selects the desired channel from many equal strength signals. Some type of optical filter is required. Coherent detection converts the optical signal to an electrical waveform and employs electronic filters to select the desired channel. This type of system is capable of very good performance, but a price is paid in terms of receiver complexity to obtain high resolution. In other systems, actual optical filters are used, but the resolution achievable here is typically only about 0.1 nm.

A unique method of high-resolution filtering is made possible by the nonlinearities of the fiber transmission medium itself. As the optical power in a single mode fiber increases, the first nonlinear optical effect that occurs is stimulated Brillouin scattering. In this effect the laser light propagating in the fiber is backscattered by an acoustic wave in the glass, which is generated by the light itself. The frequency of the backscattered light is decreased by the frequency of the acoustic wave, 11 GHz if the pump laser is at 1.5 μm. This frequency is determined by the wavevector matching condition for the pump wave, scattered wave, and acoustic wave. At power levels above a few milliwatts, waves propagating in the opposite direction from the pump, with the frequency of the scattered light, are greatly amplified through a parametric interaction with the pump light and acoustic wave. The acoustic phonon lifetime in silica gives this process a minimum linewidth of 17 MHz for light at 1.5 μm. However, depending on the index profile and dopants in the fiber, this linewidth can be tailored to suit the application. Gain of as much as 1000 can be achieved with pump powers of 10 to 20 mW.

In an optical network using frequency division multiplexing, the fiber running to the user has many available signals at different frequencies all propagating toward the user. If a pump laser is sent into the fiber in the opposite direction to the propagation of the signals, with its frequency tuned to be higher than that of the desired signal by an amount exactly equal to the backward Brillouin shift of the fiber, the desired channel can be amplified while leaving the other channels alone. If a standard direct detection optical receiver is then used, the desired channel can be detected without interference from the other signals. The number of channels that can be used is roughly equal to the gain, that is 1000 users for a gain of 1000. Each user tunes his pump laser to amplify the signal he desires to receive. The users may all receive the same channel or each user a different channel, depending on their needs and the type of system.

A demonstration of this channel selection technique has been performed[1] with two 1.5 μm external cavity semiconductor lasers, modulated at 45 Mb/s. The pump laser was a tunable F-center laser providing 14 mW of pump power into the fiber, providing a gain factor of 300 with a linewidth of 100 MHz. A 10 km length of fiber was used in this experiment, but fiber lengths as small as 2 km could be used with different fiber designs. The two information bearing channels could be placed as close as 140 MHz from each other while still detecting one channel with no interference from the other. This corresponds to a wavelength spacing of 10^{-3} nm.

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Continuous wave operation of Ga/As lasers on Si substrates

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Integration of optical devices (dominated by semiconductor GaAs) and electronic devices (dominated by