Multiple wavelength light source using an asymmetric waveguide coupler

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We obtained multiple wavelength light emission from a coupled waveguide structure formed from a conventional waveguide and a vertical cavity resonator. The cavity and quarter-wave mirrors are optimized to act as another waveguide, thus forming an asymmetric directional coupler. This asymmetry between the waveguide and the vertical cavity causes wavelength selectivity in the cavity light emission. By tapering the cavity, the phase-matched wavelength becomes a function of position, and pumping different regions along the length of the waveguides causes different wavelengths to be emitted from the device. We obtained narrow-band luminescences with a minimum width of 1 nm using a 75-Å quantum well in a GaAs/AlGaAs vertical cavity structure coupled to a low index polymer waveguide.

The technological importance of tunable lasers and multiple wavelength light sources has provided a strong impetus in developing new structures. For wavelength division multiplexed (WDM) communication systems, the most common approach has been to use a number of single wavelength light sources and multiplex them into one fiber. The cost and complexity would be radially reduced if one device could emit multiple independently controllable wavelengths. Since the light emission of vertical cavity surface-emitting lasers depends on the effective cavity length, arrays have been demonstrated in which the emission wavelength is different for each device. However, coupling all the elements of the array into a single fiber is still problematic. Similarly, distributed feedback laser arrays, each with a slightly different grating pitch, have also been fabricated, together with an integrated multiplexer and optical amplifier to compensate for the loss. But the complex manufacturing process may preclude their use in many optical links. Here, we describe a simple structure that may present a lower cost alternative to using multiple individual light sources in a WDM link.

The structure of the multiple wavelength source shown in Fig. 1 is related to a passive demultiplexer described previously. A GaAs quantum well forms the active material in a tapered vertical cavity resonator. The light is generated by exciting different regions of the vertical cavity structure. Because of the taper, each region has a different cavity thickness and exhibits a different light-emission pattern. At room temperature and at high excitation levels, the luminescence and gain region of the quantum wells can be quite broadband, and for a given cavity thickness each wavelength is emitted at a different angle. Unlike conventional vertical cavity structures, there is almost no light emitted perpendicular to the wafer since the resonator condition at normal incidence is outside the gain region of the quantum wells. Coupled to this vertical cavity resonator structure is another waveguide fabricated with lower index material. Of all the emission angle and wavelength combinations emitted by the resonator, only one is phase matched to this waveguide, and light of only this wavelength is transferred to the top waveguide. The wavelengths that do not couple propagate in the resonator and are absorbed in adjacent regions that are lossy. Because of the taper in the resonator, different wavelengths couple to the top waveguide at different points. The light that transfers to the top waveguide travels to the end facets with little attenuation, since the mirrors are not absorbing, and there is little coupling to the resonator at mismatched wavelengths. Thus by shifting the excitation region along the device, the emission wavelength is changed. Furthermore, by exciting more than one region, multiple independently controllable wavelengths are emitted. The device, in this basic geometry, works by modifying the spontaneous emission, and we have not included any provision for optical feedback and possible lasing.

The vertical cavity resonator in the device acts like a conventional waveguide except that distributed multilayer mirrors replace the low index claddings required for total internal reflection. Such waveguides, known as ARROW (antiresonant reflecting optical waveguides), allows the fabrication of very asymmetric guides. The wavelength selectivity of directional couplers has long been recognized, and recently narrow-band optical filters using this principle have been demonstrated in conventional waveguides. There is a trade-off between coupling length and wavelength selectivity for a given asymmetry. By using very different materials in the two waveguides, we can obtain high selectivity with a

![FIG. 1. Schematic of the multiple wavelength light source. The active material in the resonator emits at many wavelengths, but only one wavelength is coupled to the waveguide. The taper in the resonator causes different wavelengths to couple at different points, thus the pumping position determines the emission wavelength. Multiple positions can be pumped for multiple wavelength emission.](image-url)
short coupling length. Thus with a taper, we can effectively make one device consist of many different directional couplers.

To test these concepts, we fabricated structures by metal-organic chemical-vapor deposition (MOCVD) and tested their performance with optical pumping. The design thicknesses of the various layers were calculated from the equations presented in our previous work on the demultiplexer. Any transmission through the bottom mirror of the resonator represents a power loss from the device. Thus, in contrast to the demultiplexer, this mirror should have the highest possible reflectivity. Therefore, we used a relatively thick 30.5 period mirror stack with 76 nm/64 nm AlAs/Al_{0.3}Ga_{0.7}As layers. The resonator cavity, designed to be one wavelength thick, consisted of 250 nm of Al_{0.2}Ga_{0.8}As with a single 7.5-nm GaAs quantum well in the center. The quantum well was placed in the center of the cavity, where there is an antinode in the optical standing wave. The top mirror that controls the coupling between the top passive waveguide and the cavity consisted of seven mirror pairs, similar in structure to the bottom mirror. This gave a calculated coupling length of about 100 μm and a theoretical wavelength resolution of about 0.5 nm for a single mode lossless structure. The taper in the cavity was produced by the natural nonuniformity of the MOCVD growth process, with the side of the wafer closer to the center of the reactor thicker than the other side. The measured taper was about 3% per cm. To form the top waveguide, we spun on 5 μm of a photosensitive polymer, and exposed it to form a 5-μm-wide waveguide in the direction of the taper. Since the unexposed polymer has a higher index of 1.6028 compared to the exposed index of 1.5979, it forms a single mode waveguide in the lateral direction.

The device was tested by cleaving a piece about 2 cm long. This piece, at room temperature, was optically pumped from above with a continuous wave (CW) Ti:sapphire laser. The pump wavelength was adjusted to be above the band gap of the Al_{0.2}Ga_{0.8}As cavity and below the Al_{0.3}Ga_{0.7}As layers in the mirror to maximize the carrier density in the quantum well. Approximately 50 mW of pump power was focused to a 50-μm-diameter spot on the waveguide and the different curves of Fig. 2 were taken by shifting the pump region by 2-mm intervals. The light emission was monitored by simply placing a fiber at the cleaved waveguide facet. The measured power in the fiber was about a microwatt, and the spectrum was monitored with a spectrometer and a CCD array. The observed spectra of Fig. 2 show that the output peak clearly shifts as different regions are excited. To examine the effect of cavity loss, we also grew a similar wafer with a half wave cavity and six quantum wells. In this wafer with more quantum wells (QWs), the linewidths were significantly broader, and the linewidths narrowed only at high pump powers. Figure 3 shows how the peak emission sharpened as the excitation power was increased on this second wafer. To obtain high carrier densities in this part of the experiment, we used a mode-locked laser with 1-ps pulses and a 80-MHz repetition rate. The intensities shown in the figure have been normalized by the input power, thus for a linear system we would expect all the peaks to be the same height. In Figure 4 we compare the emission from the two ends of the device using the CW source, and find that the emission from the thin side was about five times as intense as that from the thick side.

The results agree with theoretical expectations. The out-
put spectrum shifts as the excitation position changes in accordance with the expected taper in the device. The linewidth obtained is a measure of the cavity finesse, which, using the equations previously derived, should be about 0.5 nm in a lossless structure, limited only by the reflectivity of the top coupling mirror ($R \sim 99\%$). However, the linewidth is increased by the absorption in the QW. In Fig. 2, we see that the full width at half maximum is a minimum at the longer wavelengths where the absorption is smaller. The absorption can, of course, be reduced by stronger pumping. This is shown in Fig. 3 for a device with six QWs, where the linewidth narrows as the pump power increases. With electrical pumping, it should be possible to invert the material over the ~100-μm coupling length and narrow the linewidth to the limit set by the top coupling mirror.

Though the first-order theory predicts equal optical power emanating from both ends of the device, in fact an asymmetry is observed (Fig. 4). This asymmetry is due to carrier induced changes in the refractive index. The generated carriers lower the refractive index and effectively decrease the size of the cavity at the excitation position. This reduces the local taper in the thinner direction and increases the taper in the other direction. Since a slower taper implies a greater transfer efficiency, we observe higher emission from the thin side of the device. The coupling length of the device has been designed to give over 90% efficiency with the natural taper. The refractive index changes increase this value in one direction and reduces it in the other direction.

The low efficiency of the device is also not surprising. Since we are optically pumping the structure, only a few percent of the incident light is absorbed in the active region under the waveguide. About one third is reflected, and the majority is absorbed in the substrate. Furthermore, the pump pattern has only a small overlap with the thin polymer waveguide. Taking these factors into account, the efficiency is similar to the measured values of more conventional microcavity light-emitting diodes. Electrical pumping of the active region should considerably enhance the efficiency since nearly all the injected carriers will enter the active region. Further optical confinement should also increase the efficiency. At present, there is no waveguide defined on the lower part of the device, and consequently, the QWs can emit at angles not collinear with the top waveguide. By lithographically defining a waveguide, we will reduce the two-dimensional photon density of states to a one-dimensional case, and restrict spontaneous emission into unwanted modes. Like other microwave devices, the challenge lies in reducing dimensions without increasing surface trap states that lead to nonradiative recombination.

There are a number of design parameters that can limit the performance. In other experiments with a multimode top ridge waveguide, we noticed that the linewidths were significantly broader, since each mode couples at a different wavelength. Furthermore, if we use strong optical pumping to lower the loss, the size of the pump region must be matched to the coupling length. Like the demultiplexer described before, one can improve the linewidth by increasing the top mirror reflectivity. The trade-off is an increased coupling length. Thus, like many WDM devices, the physical size of the chip determines the number of channels.

In summary, we have demonstrated a novel multibandwidth source, where exciting different regions of the waveguide causes emission of different wavelengths from the same aperture. Improvements, such as electrical pumping and better optical confinement, could make this a useful device for WDM links.

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