Recently, there has been a lot of interest in wavelength tunable receivers for multiwavelength network applications. A direct detection receiver with a combination of an optical preamplifier and an optical filter [1] offers possible high sensitivity and selectivity. In this work, we propose and demonstrate for the first time a novel integrated tunable receiver which integrates a traveling-wave optical preamplifier, a two-stage passive grating-assisted codirectional coupler (GACC) filter, and a photodetector. The GACC filter has been shown to have a wavelength tunability [2] an order of magnitude wider than a DBR filter. Also, the transmissive style of the filter makes it possible to cascade several optical elements to achieve the high functionality of photonic integration.

The GACC filter is implemented in a vertical twin guide structure in which the two waveguide cores are composed of different materials that creates a mismatch in propagation constants (or effective indexes) of the two waveguide modes. The corrugated grating introduces the necessary perturbation to couple the energies between the two waveguide modes. And, the wavelength at which the coupling occurs is determined by the index mismatch. The index mismatch can be altered, and thus the filter wavelength can be tuned, by changing the effective index of one of the waveguide modes, which is accomplished here by embedding one waveguide core in a pn junction and utilizing electro-optic and carrier effects to change the material index.

The device was fabricated on GaAs substrate using strained InGaAs quantum wells for optical gain and GaAs for the index tuning material operating around $\lambda = 0.98$. It was fabricated with a scheme similar to multisection DBR lasers [3]. In the passive coupler filter area, the InGaAs MQW was removed with a selective etch which stopped on a 30 Å AlAs layer. The grating depth is 500 Å and was etched in the same way to have precise control of the coupling strength. After the grating etch, the oxide was removed and a second MBE growth performed. The device has a 5 μm ridge structure with 500 μm long amplifier section, 200 μm long detector, a total coupler length of 1 mm and a coarse grating pitch of 9.8 μm.

The receiving spectra was measured with a tunable Ti-sapphire laser source which was coupled into the amplifier using a lensed fiber. With zero bias applied to the filter electrodes, the receiving passband was measured to be centered ~ 0.98 μm with a FWHM bandwidth of ~ 3 nm. A differential signal gain of 12 dB was obtained when the amplifier current increased from 20 mA to 34 mA. It is limited by the intracavity reflection and the reflection from the cleaved facet which was not AR coated. The receiver passband was tuned by applying a reverse bias to the filter electrodes and 4.3 nm tuning was obtained with a 8 V bias. Although the tuning with a reverse bias is not as large as with a forward bias, it eliminates thermal effects that can confuse the results.

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IIB-6 Ultra-High Efficiency Light-Emitting-Diode Arrays—I. Schnitzer, E. Yablonovitch, A. Ersen, A. Scherer,* C. Caneau,* and T. J. Gmitter,* UCLA, Department of Electrical Engineering, Los Angeles, CA 90024 Tel: (310) 206-1034 Fax: (310) 206-8495, E-mail: schnit@ee.ucla.edu

High efficiency light-emitting-diodes (LED's) are desired for many applications such as displays, printers, short-haul communication, and opto-electronic computer interconnects. However, there is an enormous gap between the theoretical efficiency of LED's and their actual efficiency. The internal quantum yield, η, of good quality double heterostructures can exceed 99%, as we have demonstrated recently [1]. On the other hand run-of-the-mill commercial LED's are usually only a few percent efficient. The reason for this long-standing shortfall is the difficulty for light to escape from high refractive index semiconductor. A mere 2% of the internally generated light is coupled into free space through the 16° escape cone, the rest suffering total internal reflection and risking re-absorption. The present commercial state-of-the-art, $\sim 20\%$ external efficiency in AlGaAs-based LED's, is achieved by growing a thick transparent semiconductor superstrate, and total substrate removal in a particularly clean, low-loss, optical design which can add greatly to the cost.

The key to increasing the escape probability is to give the photons multiple opportunities to find the escape cone. This requires angular randomization or scrambling of the light rays. One way to do this is by photon high self-absorption, and a very clean, non-dissipative optical design. In [1] we used the epitaxial liftoff (ELO) technique [2] to mount thin film heterostructures on high reflectivity surfaces. It was found that while the photon re-cycling can yield an ultrahigh external quantum efficiency (72%), it is very susceptible to parasitic loss mechanisms (free carrier absorption in doped layers, for example) or slight degradation in the internal quantum efficiency. A more practical approach, and the one which we propose here is the angular randomization by elastic scattering of the photons from a textured semiconductor surface.

Our approach has two components: i) separation of thin-film heterojunctions from the growth substrate using the ELO technique, and ii) nano-texturing of the thin-film semiconductor interface by natural lithography [3]. The implementation of these two components leads to a thin film (< 1 μm) geometry in which one side of the heterostructure is facing a high quality reflector while the other surface, the semiconductor/air interface, is textured to act as a strong scatterer. This geometry employs the statistical mechanical concept of phase-space filling by angular randomization. We invoke a statistical approach [4] to model the smooth and textured film geometries. It is concluded that the textured film geometry can boost the external efficiency to 50% or more, while relieving the demand for the utmost material quality, high self-absorption, and low parasitic losses, as required by the smooth film geometry of Ref. 1.

The actual LED structure is a conventional n^+-AlGaAs/p-GaAs/p^+-AlGaAs double heterostructure, grown over a 0.05 μm thick AlAs release layer by organometallic chemical vapor deposition. Large LED's arrays are fully processed from these wafers, then separated from the GaAs substrate by epitaxial liftoff, and Van der Waals bonded by surface tension forces onto large area dielectric coated Au mirrors. To minimize the likelihood that light will be parasitically absorbed at the Ohmic contacts, a significant problem in all LED's, we have employed the concept of current crowding. Carriers are injected into a central region between the two Ohmic contacts, but reasonably distant from either contact. The final processing step is the texturing of the light emitting region. The surface of the LED is coated by a randomly close-packed array of polystyrene spheres, 0.2 μm diameter, using the surface forces between the charged spheres and the semiconductor. The spheres then act as an etch mask for a Cl_2 assisted Xe^+ ion beam etching, about 0.17 μm deep.

The light versus current characteristics of these LED's have been measured and modeled. We have observed 9% external quantum efficiency from untextured LED's array transforming into **30% external quantum efficiency** following the surface texturing treatment. We conclude that by employing the principle of phase-space-filling in an improved device geometry, 56% efficient LED's arrays can be expected. Such LED's are simpler and more reliable than lasers. Unlike lasers they are thresholdless, yet they offer comparable external efficiency. Moreover, the principles and the device geometry that we are proposing can be applied to other semiconductor material systems to obtain very bright visible thin film, top processed, LED's arrays as well. It is clear that the availability of 30%–50% efficient, low-cost, reliable, visible LED's would change dramatically the appearance of our homes, offices, and streets.

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IIB-7 Pseudomorphic SCH Blue-Green Diode Lasers—D. C. Grillo, Y. Fan, M. D. Ringle, J. Han, L. He, R. L. Gunshor, H. Jeon,* A. Salokatve,* M. Hagerott,* A. V. Nurmikko,* G. C. Hua,** N. Otsuka,** E. Oh,*** and A. K. Ramdas,*** School of Electrical Engineering, Purdue University, West Lafayette, IN 47907 (317) 494-3509.

The first blue-green diode lasers were reported by 3M (at the DRC) and the Brown/Purdue group in the summer of 1991. Two types of device configurations were employed for the earliest structures. 3M used a single quantum well approach where the optical confinement was provided by an intrinsically nonpseudomorphic structure having dislocation arrays between the Zn(S,Se) cladding layers and the ZnSe barrier regions. A second type of structure, which we described at the 1992 DRC, was pseudomorphic and contained multiple quantum wells of (Zn,Cd)Se which served as a compromise between optimum electrical and optical confinement. The optical confinement for such MQW structures was relatively weak. In August of 1992 Sony reported the use of the quaternary (Zn,Mg)(S,Se) in a diode laser operating at 77 K. Such a quaternary compound can maintain lattice compatibility to GaAs with increased bandgap for the implementation of separate confinement heterostructure (SCH) QW lasers. In this talk we will describe our efforts to employ the quaternary in pseudomorphic SCH diode configurations. These preliminary devices (without heat sinking or coated facets) have been operated at room temperature under pulsed conditions (~ 1 μs, 10^{-3} duty cycle) for periods exceeding 1/2 h before failure. A group at Phillips laboratories has recently obtained nearly 400 K operation with 10 to 50 ns pulses in a similar strucuture. Achieving pseudomorphism requires specific choice and control of Mg and S fractions necessitating precise flux measurement. A combination of PL, X-ray diffraction, and electron microprobe analysis was employed to determine alloy fractions. The addition of Mg into Zn(S,Se) seemed to have a significant effect on lattice dynamics; FWHM values from X-ray rocking curves were above 350 arcsec when alloy composition was adjusted to place the lattice parameter of a relaxed alloy just below that of GaAs, the condition for optimum design of a pseudomorphic Zn(S,Se) layer. With the lattice parameter of the quaternary increased to a value above that of GaAs, FWHM values of as low as 60 arcsec, consistent with TEM images showing few dislocations or stacking faults, were obtained for a laser structure employing quaternary cladding layers (Mg = 9%, S = 12%). The diode laser devices had a single (75–100 Å) (Zn,Cd)Se quantum well, 1500–2000 Å Zn(S,Se) confinement layers, and 1–1.5 μm quaternary cladding layers. The Zn(Se,Te) graded contact scheme, first reported last summer as a low-resistivity ohmic contact to p-ZnSe-based devices, was adapted to make ohmic contact to the quaternary p-type cladding layers. LED action was observed below three volts of bias, and lasing was obtained at 15 V with a gain-guided structure at room temperature. Room temperature LED devices were operated CW at up to 300 A/cm^2 indicating a possibility for obtaining room temperature CW laser operation.

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