Ultra-Low Anti-Reflection (AR) Coating for High-Power External Cavity Diode Lasers (ECLs)

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ABSTRACT

Frequency tunable transmitters such as external cavity diode lasers (ECL) are key to the incipient next generation of optical telecommunications networks. Ultra-low anti-reflection (AR) coating on one facet of a laser diode (gain medium) in an ECL enables the required combination of high power, wide tuning range, and spectral purity. With an optimized design and careful deposition process control, such high quality coatings may be obtained with conventional optical coating materials such TiO_2, Ta_2O_5, ZnS, SiO_2, SiO, MgF_2. In this paper, we discuss design requirements, deposition methods, equipment compatibility, and film thickness control capability necessary to achieve a reflectivity of $\leq 5x10^{-4}$ over the a wavelength range that spans both the C and L bands.

INTRODUCTION

With advances in dense wavelength division multiplexing (DWDM) technology over the past few years, the need for wavelength-agile tunable lasers has increased dramatically. Widely tunable lasers have the potential to revolutionize optical networks with the promise of new flexibility, enhanced network functionality, and cost savings. The applications driving the development of tunable lasers include test and measurement for network component manufacturing, system inventory management, sparing, hot backup and fixed-wavelength laser replacement, and also the significant capacity increase with reconfigurable optical add/drop multiplexers (OADM), wavelength routing and conversion, and packet switching in the advanced optical network [1].

There are four major technological approaches to tunable laser development including distributed feedback (DFB), distributed Bragg reflector (DBR), vertical cavity surface emitting laser (VCSEL), and external cavity laser (ECL). Each technique has its own merits and the most suitable choice will be dependent on the application. The external cavity tunable laser (ECL) has been employed in testing and measurement applications, and may become a key component for next generation optical network due to its combined superior features of high power, wide tuning range, narrow linewidth, excellent spectral purity, and high side-mode suppression ratio (SMSR). Single-mode operation, the condition when a laser operates in a single optical frequency in a single spatial mode, is a basic design requirement of the ECL for achieving such combined superior features. One important parameter affecting single-mode operation of an ECL is the facet reflectivity [2]. A suitably low facet reflectivity across the entire tuning range guarantees that laser will operate in the strong feedback regime-where the external cavity determines the mode operation of the laser. Ultra-low reflectivity AR coating is a key process to producing a high-power, broadly-tuning ECL. The aim of this report is to exhibit the fundamental AR coating development work for such lasers.

AR COATING DEVELOPMENT

AR modeling

Modeling for AR coating was done with a TFCalc commercial package from Software Spectra, Inc. with the following parameters considered at the outset:

- Materials effect on reflectivity bandwidth
- Waveguide (WG) index of refraction (n) effect on target film thickness
- Operation window of film thickness
- WG index n effect on reflectivity bandwidth

Wideband AR performance may be achieved with different coating designs. A two-layer design is a common starting point that results in a fairly simple process but typically yields a narrow-bandwidth V-shaped AR coating. Obtaining a wider bandwidth requires multi-layer film structures. However, in order to accurately model such designs, the laser waveguide index of refraction must be accurately known.

Figure 1 shows predicted performance of a 2-layer AR coating illustrating materials effects on bandwidth. Note that a larger gap between high and low index materials will generate wider bandwidth. In this modeling work, the indices of refraction at 1550 nm are taken to be 2.246, 2.230, 2.015, 1.608, 1.453, and 1.372 for ZnS, TiO_2, Ta_2O_5, Al_2O_3, SiO_2, and MgF_2 respectively.

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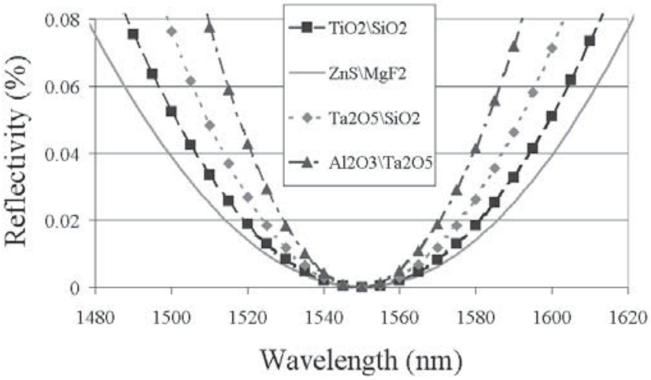

Figure 1: Effect of materials on bandwidth. Modeling results from 4 pairs of 2-layer AR coating design, $ZnS\backslash MgF_2$, $TiO_2\backslash SiO_2$, $Ta_2O_5\backslash SiO_2$, $Al_2O_3\backslash Ta_2O_5$.

Deposition process

All optical coatings were processed in a chamber modified from Varian 3125 horizontal vacuum chamber with an ion-assisted deposition (IAD) process. The chamber is equipped with the following deposition instrumentation:

- Arc-free E-gun system for materials evaporation
- Ion source for film densification
- Ellipsometer for in-situ film thickness and n index monitoring
- Film deposition controller for deposition rate control
- Cryopump for high vacuum pumping.

The chamber is routinely pumped down below 10^{-7} torr before any deposition. To produce dense anti-reflection (AR) coating and preserve film stochiometry we used ion energies of 40 ~ 80 eV for the IAD process. Deposited films on Si substrate are analyzed by a commercial n&k 1200 analyzer, which give film thickness as well as both real and imaginary indices of refraction (n, k) simultaneously. The analyzer is able to collect data from 190 ~ 1000 nm and extrapolate n and k data up to 3000 nm wavelength. Figure 2 shows examples of n and k spectra from the n&k analyzer. The results for TiO_2 and SiO_2 in the figure are very similar to previously reported data [3].

During the coating process, laser diodes are mounted onto a holder and coated with 2-layer or multi-layer dielectric films. The layout of target, source and ancillary hardware is designed to minimize fixture shadowing and the geometric impact on film thickness and deposition uniformity.

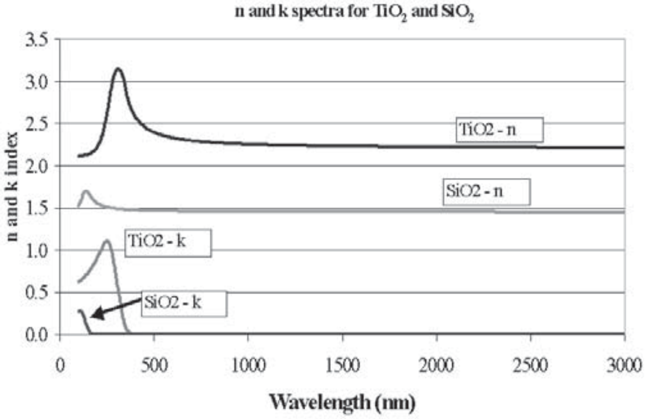

Figure 2: Sample spectra of real and imaginary indices of refraction (n and k respectively) for TiO_2 and SiO_2 films

RESULT AND DISCUSSION

AR coating performance

After coating, the AR performance is characterized as follows: a curve of optical power versus current (P-I curve) along with a spectrum of amplified spontaneous emission (ASE). These data are analyzed by comparison to baseline measurements made prior to coating. One example in Figure 3 shows the coating effect on laser optical performance with a typical Fabry-Perot laser. Before AR coating the diode laser displays characteristic lasing behavior due to the feedback of diode facet with a distinct threshold current (I_{th}) at around 6 mA. The diode loses its lasing capability after AR coating and behaves as a light emitting diode (LED). Lasing capability is later re-established in the ECL via feedback from an external retroreflector.

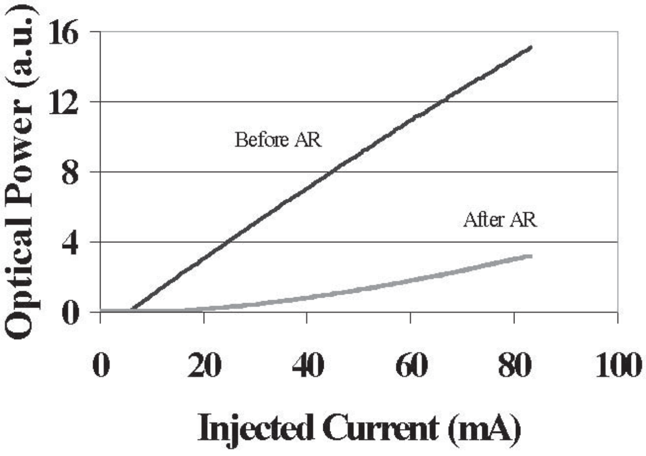

Figure 3: AR coating effect on PI curve

Figure 4 illustrates AR coating effect on ASE performance. These ASE spectra are taken at sub-threshold currents (i.e., $I<I_{th}$). The periodic amplitude modulation evident before AR coating is due to the native reflectivity (R~30%) of the uncoated laser diode facets. AR coating of one facet reduces the reflectivity to $<5x10^{-4}$, while a conventional coating is typically applied to the second facet to provide an enhanced reflectivity tailored to a given external cavity design [4]. The ultra-low reflectivity on the laser facet suppresses the self-lasing operation within the diode's internal cavity. Note that the small modulation evident in the post-coating ASE spectrum has the same period seen in the initial spectrum and is due to the residual facet reflectivity.

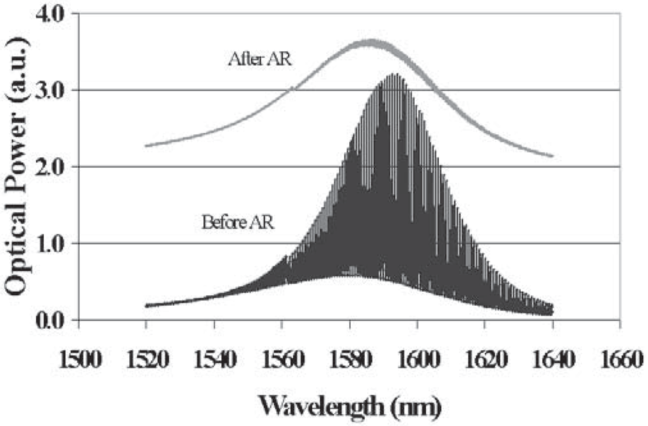

Figure 4: AR coating effect on ASE spectra

Measurement of the Facet Reflectivity

Direct methods lack sufficient sensitivity to measure this ultra-low reflectivity on a laser facet. However, various indirect methods have been developed over the last two decades [5][6][7]. In this work the spontaneous emission transformation (SET) method developed at the University of Maryland [8] is employed. This method provides a high signal to noise ratio (SNR) by transforming the ASE spectra into the Fourier domain in which the signal components are orthogonal to most of the noise. Figure 5 exhibits the comparison between the result from SET method and from TFCalc modeling. Experiment and theory are in good agreement in the long wavelength portion of the spectrum. The discrepancy observed at shorter wavelengths is believed to be mainly due to low ASE signal and hence poor SNR in this region.

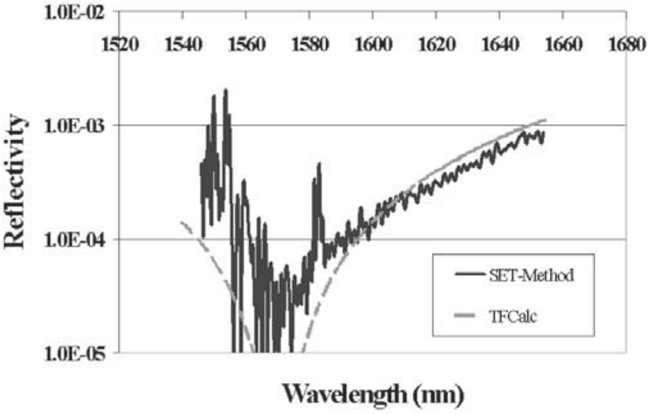

Figure 5: Comparison of theoretical (TFCalc) and experimental (SET) AR coating performance

ECL optical performance

An ECL optimizes the relation between gain and feedback elements to produce maximum output power over a wide tuning range. Figure 6 shows the tuning capability of an ECL designed for test and measurement applications. Note that the range extends from the low end of the C-band (1520 nm) to the high end of L-band (1620 nm). This wide tuning range is particularly valuable for high-volume testing and measurement of high-performance WDM components.

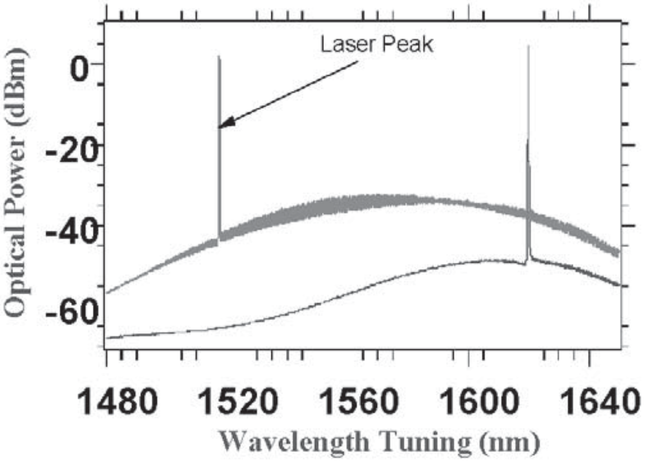

Figure 6: ECL single-mode operation across C and L bands

Figure 7 exhibits high output power (20 mW) over the whole C-band (1520 to 1570 nm) from a network tunable laser. This high output power allows long-haul and ultralong-haul systems makers to cover longer span distance, minimizing the need for signal regeneration.

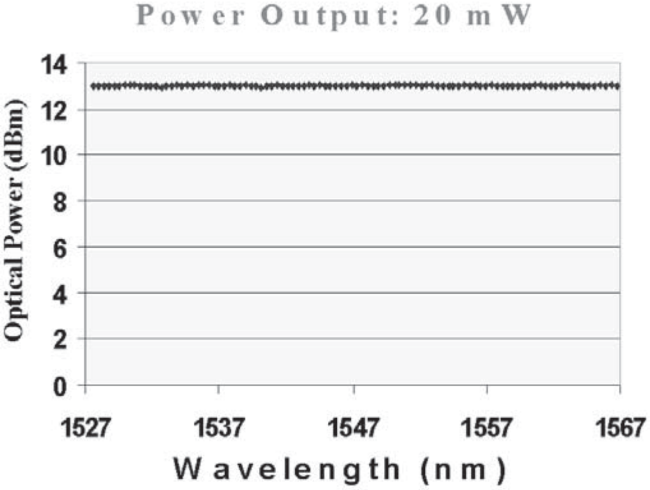

Figure 7: High output power over the entire C-band

Figure 8 shows two other important laser performance parameters: high side-mode suppression ratio (SMSR) and narrow linewidth. This spectral purity is important in network applications for minimization of cross-talk and bit-error rates and is also essential in test and measurement applications [9].

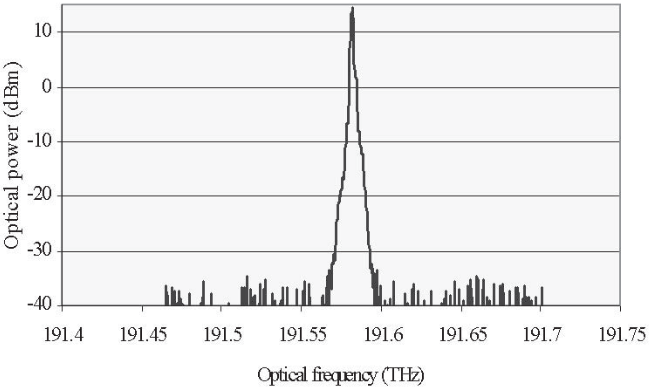

Figure 8: Side mode suppression ratio and unmodulated linewidth obtained from an ECL employing ultra-low reflectivity coating on one facet of the laser diode gain medium.

CONCLUSION

Laser diode facet reflectivities of ≤ $5x10^{-4}$ across the C+L bands can be achieved with a 2-layer AR coating using conventional materials. With this level of coating performance the laser gain element in ECLs can be a common Fabry-Parot device that is readily available in many wavelengths including optical telecommunications S-band and L-band ranges. Such an ultra-low AR coating plays a key role in producing high-quality tunable ECL systems with high output power, wide tuning range, and high spectral purity, and enables low-cost, high-performance tunable lasers for next-generation optical networks.

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