Hybrid ECL/DBR wavelength & spectrum stabilized lasers demonstrate high power & narrow spectral linewidth

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ABSTRACT

The use of $LiNbO_3$ based Volume Holographic Gratings (VHGs) to provide spectrally filtered feedback to a semiconductor laser diode was documented in the mid 1980s[1], however issues with long term stability had left this technology on the sidelines. Photo-sensitive glass based VHGs do not exhibit long term aging or thermal/photo bleaching effects, and therefore have enabled a new type of External Cavity Laser (ECL). This highly manufacturable "hybrid ECL/DBR" (HECL) laser utilizes precision VHGs and has been used to create high performance lasers with spectrally tailored output. Lasers with fiber coupled output powers in excess of 4.2 W and spectral line widths of less than 0.15 nm have been demonstrated. Additionally, multi-mode lasers have been developed for High Resolution Raman Spectroscopy that exhibit spectral line widths below 0.06 nm (i.e. < 1 wavenumber) with fiber coupled output power in excess of 350 mW. The use of glass based VHGs provides HECL laser wavelength stabilization of better than 0.01 nm/^oC, and allows the production of lasers at virtually any wavelength between 650 nm – 2400 nm.

Keywords: Hybrid External Cavity Laser, Wavelength & Spectrum Stabilized Laser, Volume Holographic Grating, Holographic Volume Bragg Grating

1. INTRODUCTION

Semiconductor diode based External Cavity Lasers (ECLs) that utilize spectrally filtered feedback to select the specific laser operating wavelength have been a core component in many precision systems, and can be found in many application areas ranging from Raman spectroscopy sources to fiber optic communications links. Traditional diode based ECL technologies rely on surface gratings (ruled or holographic) or on Bragg gratings located within the optical fiber (commonly referred to as Fiber Bragg Gratings or FBGs). These techniques have the advantage of being able to select a desired operating wavelength, however, they exhibit large wavelength shifts as a function of temperature and therefore require the use of Thermo Electric Coolers (TECs) to accurately maintain "lock" on the desired operational wavelength. Furthermore, these systems are often sensitive to mechanical vibration and shock and therefore are not suitable for harsh operational environments. To address these limitations, a methodology to leverage the benefits of the diode based ECL while limiting its drawbacks has been developed in the form of the Hybrid ECL/DBR Laser (HECL).

The use of $LiNbO_3$ based Volume Holographic Gratings (VHGs) to provide spectrally filtered feedback to a semiconductor laser diode in an external cavity laser (HECL) configuration was detailed by Accuwave Corporation in 1993[2]. Reflection mode VHGs (also called Volume Bragg gratings (VBGs), Bragg mirrors, bulk Bragg gratings, or 3-D Bragg gratings) utilize a photosensitive bulk material in which a periodic change in index of refraction can be can be permanently recorded. $LiNbO_3$, dichromated gelatin films, and polymers were the primary bulk materials of choice, however issues with long term stability of the Bragg grating in these substrates had until recently left this technology on the sidelines. The continued search for reliable and homogeneous substrate materials for use in the recording of permanent holographically formed volume Bragg gratings has lead to the development of photo-sensitive glass based VHGs that do not exhibit long term aging or thermal/photo bleaching effects. This novel and reliable glass based VHG technology provides the means to produce highly stable reflective gratings that can be tailored in a manner that allows the laser designer to select both the specific operating wavelength and spectral bandwidth. Chirping or apodizing the

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grating within the glass can further define the exact filter shape and enables the creation of an even wider range of spectral profiles to match specific application needs.

This highly stable glass material, along with high volume manufacturing techniques and methods of identifying defects in the bulk substrate, has enabled the commercial implementation of a new type of external cavity laser. The Hybrid ECL/DBR Laser (HECL) utilizes standard Fabry-Perot style laser diodes in an external cavity Distributed Bragg Reflector (DBR) configuration (Figure 1) and enables the manufacture of lasers that can be locked to a specifically designed wavelength, with spectrally tailored linewidths and a high degree of wavelength stability over temperature.

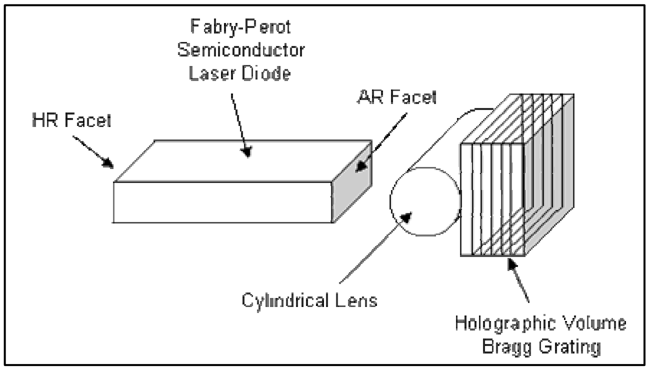


Figure 1. Hybrid ECL/DBR Laser (HECL)

The use of HECLs offers system engineers a semiconductor laser solution with significant performance and system design advantages over traditional techniques. Lasing wavelength can be accurately selected and repeatedly delivered to within 0.1 nm for virtually any desired wavelength between 600 nm and 2400 nm. Spectral linewidth (FWHM) can be tailored between 0.06 and 0.5 nm to create sources with exceptionally high spectral brightness, wherein virtually all of the output power of the laser is contained within a defined wavelength band and side mode suppression ratios (SMSRs) can be better than 50 db. Wavelength stability over temperature is reduced to less than 0.01 nm/^{o}C, which often allows for the elimination of low efficiency TECs from the system design and enables the development of battery operated systems with enhanced portability. Elimination of precision machined mechanical components and FBGs dramatically reduces the effects of shock and vibration on laser stability and offers the ability to introduce HECLs into systems for use in harsh environments. Finally, exceptionally high output power levels are attainable (>4.2 W from a single emitter operating at 976 nm has been demonstrated) and systems can be scaled to leverage both geometric and WDM coupling methodologies to achieve even higher output power levels. These advantages offer the opportunity to dramatically reduce system size, weight, and total power consumption thereby enabling the development of a wide range of novel systems for use in spectroscopy (Raman, FTIR, absorption, and ring down), high efficiency optical pumping (for both solid state and fiber lasers), illumination, medical imaging and diagnostics, and surgical applications.

The performance advantages of the HECL systems detailed above are made possible by the advent of highly reliable and homogeneous photo-sensitive glass with minimal inclusions, surface defects, and grating uniformity. Recently introduced manufacturing practices have dramatically improved both within lot and lot to lot variations of wavelength and spectral bandwidth variance between VHG elements, while maintaining consistent physical dimensions from lot to lot. This process enables the delivery of highly repeatable laser performance with minimal manufacturing impact, and allows the use of VHGs at virtually any wavelength with any desired reflectivity. Furthermore, the high degree of manufacturing consistency eliminates the need to re-tool the HECL manufacturing process thereby enabling the manufacture of custom wavelength HECL solutions in a standard production line format.

2. METHODOLOGY & RESULTS

The HECL devices discussed herein were manufactured with standard Fabry-Perot laser diodes whose normal lasing wavelengths were within approximately 10 nm of the desired “locked” wavelength value. These laser diodes were coated with high reflectivity facet coatings on one facet and low reflectivity (AR) coatings on the other in order to suppress stand alone lasing and to allow the spectrally filtered feedback from the VHG to function as the laser’s output mirror. The VHGs utilized were manufactured by Ondax Corporation, and featured a variety of wavelengths and spectral bandwidths. The cavity design is schematically represented in Figure 1. The use of the VHG as a spectrally filtered feedback source in this manner allows the broad spectrum light emanating from the laser to be filtered and retro-reflected back into the semiconductor laser. This action “locks” the laser to a selected wavelength and allows only the Fabry-Perot modes resonating within the spectral bandwidth of the filter to be sustained, thereby allowing the HECL designer to both accurately select the laser’s wavelength and tailor the laser’s spectral linewidth. Figure 2a and 2b depict the optical spectrum of a typical Fabry-Perot laser diode both with and without the spectrum stabilization resultant from the use of a VHG in a HECL cavity.

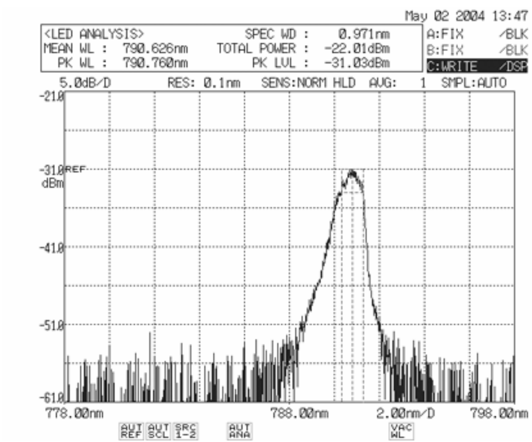


Figure 2a. Free Running Fabry-Perot Laser

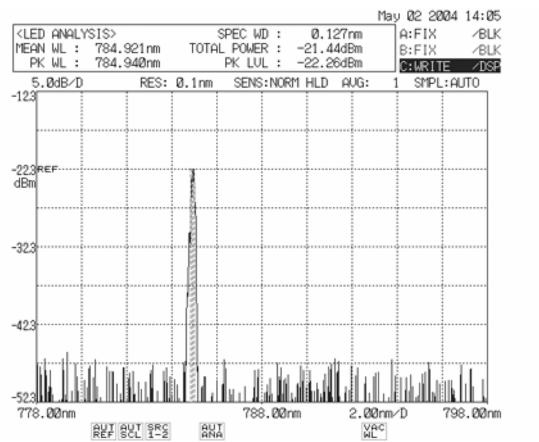
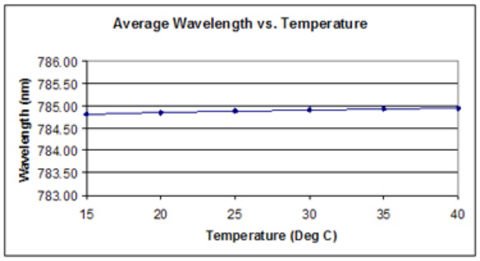


Figure 2b. Spectrum Stabilized Fabry-Perot Laser in HECL Configuration

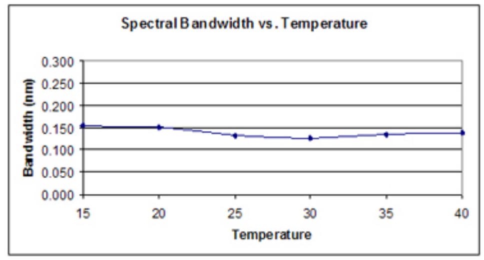
As depicted in Figure 2a, the lasing wavelength of a typical 785 nm laser can range between 780 and 790 nm and exhibits a typical spectral linewidth on the order of 1 nm. As can be seen in Figure 2b, the use of the same laser diode along with a VHG in an HECL configuration allows for both accurate wavelength selection and spectral narrowing.

An additional benefit resultant from the use of the VHG in an HECL configuration is the reduction of the influence of the effective index of refraction change in the laser chip due to changes in temperature. By extending the cavity and utilizing materials with low coefficients of thermal expansion, the ratio of change in effective index between a standard Fabry-Perot laser diode and a HECL can be dramatically reduced. This characteristic allows HECLs to be designed that are between 30 and 70 times more thermally stable than traditional Fabry-Perot laser diodes and wavelength stability better than 0.01 nm/^{0}C can be achieved. Figures 3a-d detail both the wavelength and spectral linewidth as a function of temperature and current for a standard 600 mW Spectrum Stabilized 785 nm Raman source laser.

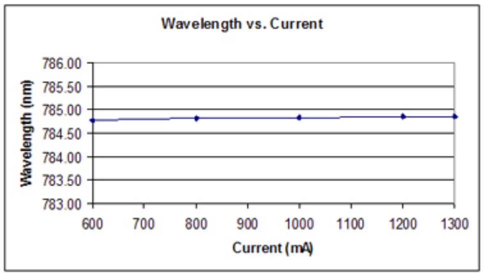
The overall performance of the HECL devices detailed herein is highly dependant upon the quality of the VHG material. Spectral characteristics including spectral linewidth (FWHM) and side mode suppression ration (SMSR) are particularly sensitive to grating defects, specular surface reflections, and variations in the material photosensitivity that manifests as a localized change in the grating coupling efficiency. Since these performance characteristics are critical to many applications, it is imperative that each grating be carefully screened in order to maintain a high degree of reliability and repeatability in spectral performance from HECL device to device.



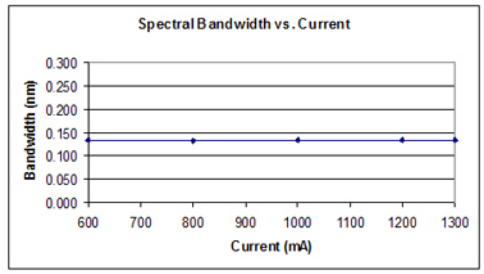
3a. Average Wavelength Change vs. Temperature



3b. Spectral Linewidth Change vs. Temperature



3c. Average Wavelength Change vs. Current



3d. Spectral Linewidth Change vs. Current

Recent developments in VHG manufacturing, testing, and inspection are routinely providing consistently high quality component parts with small variance of wavelength, spectral bandwidth and reflectivity both within a lot and from lot to lot.[3] The high degree of uniformity of both wavelength and efficiency (reflectivity) across a wafer (detailed in Figure 4) has dramatically reduced HECL manufacturing variance and allows for the delivery of laser components that appear virtually identical to OEM customers.

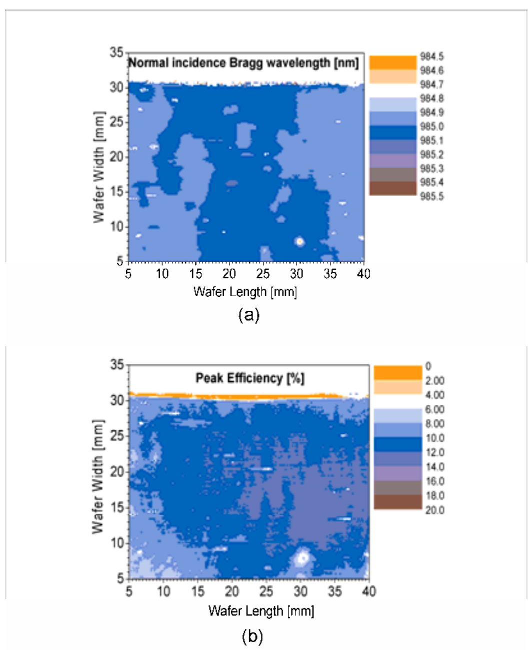


Figure 4. VHG wafer testing: 250 μm resolution measurement across 30 x 40 mm wafer. (a) map of normal incidence Bragg wavelength. (b) Map of peak diffraction efficiency

Figure 5 details a series of nine (9) HECL lasers manufactured from a single VHG lot. As can be seen, the standard deviation on both wavelength and spectral bandwidth are very low, indicating a high degree of manufacturing consistency.

IPS Laser ID #	λ at 25 C	Δλ at 25 C	λ at 1000 mA	Δλ at 1000 mA
264	784.8	0.152	784.8	0.14
315	784.84	0.158	784.8	0.132
316	784.86	0.139	784.84	0.134
324	784.86	0.163	784.82	0.14
326	784.88	0.141	784.84	0.157
332	784.84	0.156	784.82	0.141
346	784.78	0.188	784.76	0.123
347	784.86	0.147	784.78	0.14
348	784.84	0.137	784.78	0.132
Average	784.84	0.153	784.80	0.138
Minimum	784.78	0.137	784.76	0.123
Maximum	784.88	0.188	784.84	0.157
Standard Deviation	0.0316	0.0158	0.0279	0.0093
Variance	0.0010	0.0002	0.0008	0.0001

Figure 5. HECL Manufacturing consistency within VHG lot

This data is expanded in Figure 6 to include an examination of the manufacturing consistency from lot to lot. This data set includes a series of forty two (42) HECL lasers manufactured from five (5) different lots.

	λ at 25 C	Δλ at 25 C	λ at 1000 mA	Δλ at 1000 mA
Average (42 samples)	784.70	0.143	784.68	0.139
Minimum	784.28	0.126	784.24	0.123
Maximum	784.90	0.188	784.86	0.181
Standard Deviation	0.2133	0.0133	0.2157	0.0116
Variance	0.0455	0.0002	0.0465	0.0001

Figure 6. HECL Manufacturing consistency between VHG lots

This high degree of manufacturing consistency offers the system developer the potential for large cost savings by dramatically reducing laser characterization operations and eliminating the “scrap” and required overage purchases associated with typical Fabry-Perot lasers.

3. FOCUS ON APPLICATIONS

The need for highly spectrally stable lasers in the visible and near IR wavelength regime that feature both high output power and high spectral brightness characteristics, offers the opportunity to apply HECL technology to applications such as solid state and fiber laser pumping, Raman spectroscopy, illumination, medical imaging and diagnostics, and surgical applications. As a result, fiber coupled and open beam laser modules with output powers in excess of 4.2 W (fiber coupled) at a wide variety of wavelengths are now available as standard products for both Original Equipment Manufacturers (OEMs) and researchers.

The need to customize spectral characteristics such as wavelength, spectral linewidth, SMSR, or fiber type for a wide variety of applications has fostered the development of a modular system approach to enable the spectral tailoring of lasers to meet specific system needs. The spectrum detailed in Figure 7 below depicts an ultra-narrow spectral linewidth Raman source laser with over 600 mW of output power from a 100 μm optical fiber. This custom laser required a spectral linewidth < 0.06 nm and a high Side Mode Suppression Ratio (SMSR up to -50 dB) in order to meet the stringent requirements of a particular high resolution Raman spectroscopy application. The laser developed utilized standard HECL components in a modular format, and ultimately allowed the system developer to provide a diode based instrument capable of resolving less than 1 wavenumber (< 1 cm^{-1}).

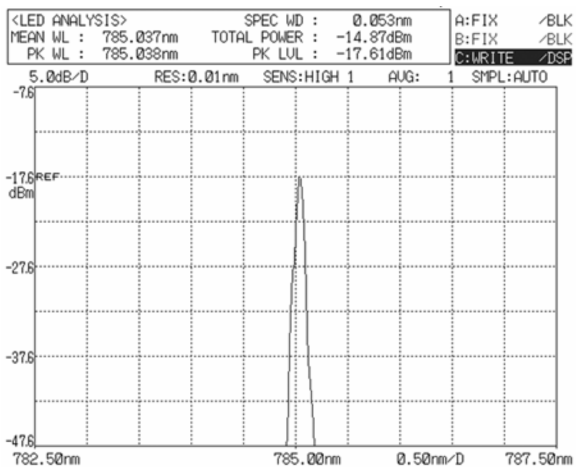


Figure 7. Spectral Plot of Ultra-Narrow Spectrum Stabilized 785 nm Multi-Mode Laser Designed for High Resolution Raman Spectroscopy Applications

Figure 8 below depicts the spectral profile and LI curve of a HECL laser operating at 976 nm with an output power greater than 4.2 W in 100 μm core optical fiber. This source was packaged in an uncooled 14-pin butterfly package and was specifically designed to meet the needs of the laser pumping industry. This laser's tailored spectral bandwidth provides the system designer with exceptionally high spectral brightness and dramatically improves pumping efficiency. The inherent wavelength stabilization of the HECL reduces the thermal control requirements normally placed on the pump laser and increases the pump laser lifetime and reliability by assuring that the laser remains "locked" at the desired pumping wavelength regardless of ambient temperature or aging effects of the laser diode.

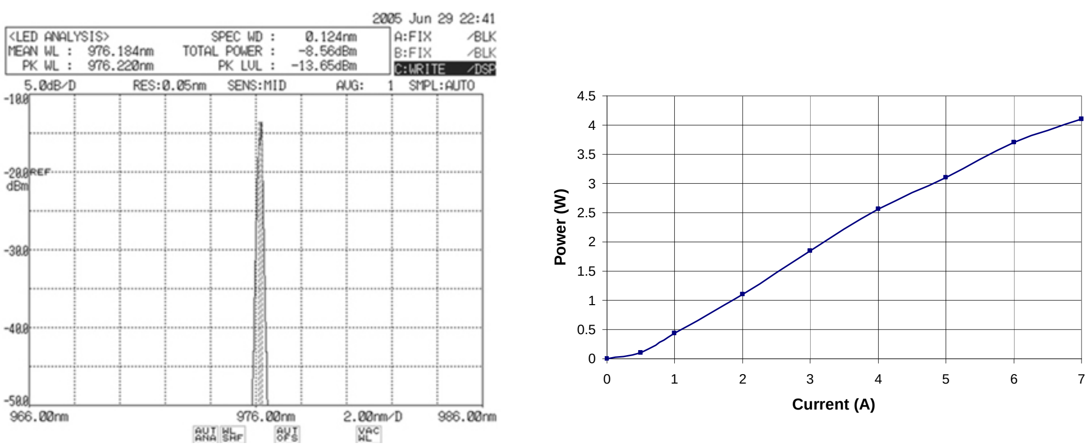


Figure 8. Spectral Plot and LI Curve of High Power/High Spectral Brightness 976 nm Spectrum Stabilized Laser

Other applications that can leverage the performance enhancements afforded by the HECL designs include battery operated low resolution Raman spectroscopy systems and FTIR systems designed for use in harsh environmental conditions. In the former, uncooled HECLs can be built into standard 14-pin butterfly packages (Figure 9), thereby eliminating the least efficient component (the TEC) and allowing for the integration of source lasers that output over 400 mW in a 100 μm optical fiber with less than 2.5W total power consumption. This enables the development and commercialization of low cost, light weight, battery operated systems and allows Raman spectroscopy to be considered for a wide variety of commercial applications that were previously unrealistic entry points due to portability, weight, and cost constraints. In the latter, the elimination of vibration sensitive FBGs and mechanical components such as ruled gratings allow HECLs to be placed in manufacturing environments without the need for added environmental conditioning enclosures. This decrease in system complexity reduces cost, simplifies maintenance, and reduces system weight thereby improving technology adoption and easing system integration efforts.

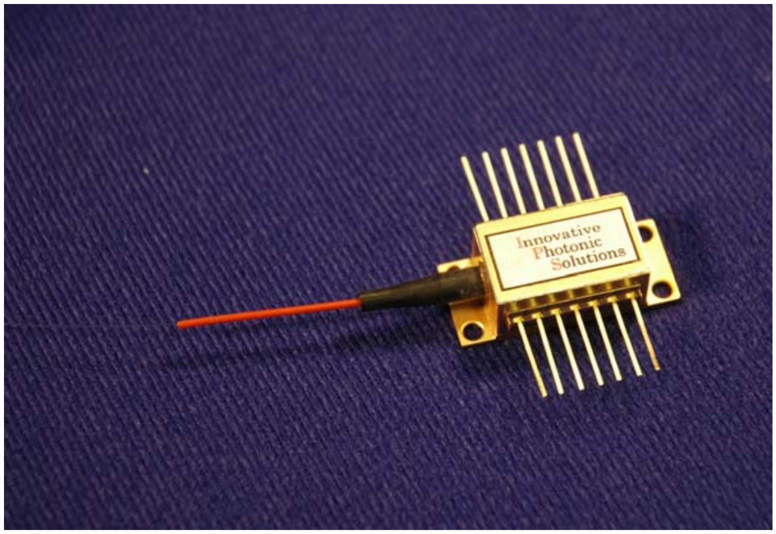


Figure 9. Fiber coupled HECL in a 14-Pin butterfly package

Finally, applications requiring tailored spectral linewidths can benefit from the HECLs ability to "slice out" only the desired portion of the optical spectrum. This "spectral slicing" has the potential to offer system designers the opportunity to build systems that operate near (or even straddle) undesirable water (or gas) absorption lines. It allows for the development of complex spectral profiles that can be used in absorption spectroscopy applications to create highly accurate sensing systems. The ability to spectrum slice also provides benefits to both solid state and fiber laser manufacturers in that the acceptance band of the pumped media can be spectrum matched thereby optimizing pumping efficiency and decreasing parasitic system heating.

4. CONCLUSIONS

The use of glass based Volume Holographic Gratings in a HECL configuration offers system designers a wide variety of performance enhancements including accurate wavelength selectivity with a high degree of thermal stability, SMSR > 50 dB, selectable spectral linewidths from 0.5 nm to 0.06 nm, high output power levels, and the opportunity to create battery operated systems with low power consumption. The reliable and repeatable delivery of HECLs with these characteristics is highly dependent upon the manufacture of VHG elements from homogeneous glass substrates with minimal surface and volume defects. New VHG manufacturing and testing techniques have enabled the delivery of extremely consistent HECL device characteristics. This repeatability reduces the incoming characterization effort normally required at the system manufacturer's facility and therefore reduces cost and allows for a dramatic reduction in typical sparing and scrap levels. The manufacturability enhancements coupled with the superior spectral performance of the HECL has enabled their adoption and integration into a wide variety of optical systems for applications including spectroscopy (Raman, FTIR, absorption, and ring down), high efficiency optical pumping (for both solid state and fiber lasers), illumination, medical imaging and diagnostics, and surgical applications. The ability to custom tailor wavelength and spectral linewidth, coupled with the scalability of power in HECL systems, further increases the number of applications and system designs that can be conceived of by applications engineers.

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