Spatio–Spectral Mapping of Multimode Vertical Cavity Surface Emitting Lasers

Kevin J. Knopp, Student Member, IEEE, Student Member, OSA, David H. Christensen, Greg Vander Rhodes, Joshua M. Pomeroy, Bennett B. Goldberg, Member, IEEE, and M. Selim Unlu, Senior Member, IEEE

Abstract—This paper reports the spatial and spectral characteristics of multimode vertical cavity surface emitting laser (VCSEL) emission using near field scanning optical microscopy (NSOM). We have investigated 15 μm diameter proton implanted 850 nm devices used in 2 Gb/s multimode fiber optic links. We have studied their near field spatial distribution of intensity and the lasing wavelengths of their transverse modes. False colored images were created to portray relative intensity, and spatial distribution information for each transverse mode. Correlation with shear force data allowed mapping of the optical distributions to topographical features of the device. Lasing filaments were observed at high drive currents. Spatially overlapping transverse modes were observed to compete for available gain while spatially isolated modes coexisted.

Index Terms—Microscopy, near field, spectral spatial mapping, transverse modes, vertical cavity surface emitting laser (VCSEL) mapping.

I. INTRODUCTION

VERTICAL cavity surface emitting lasers (VCSEL’s) hold tremendous promise in applications of optical interconnects, optical processing, and high-speed, short-haul optical communications. Their promise arises out of the orientation of their optical cavity normal to the semiconductor wafer on which they are grown [1]. As a result of this orientation, VCSEL’s have circular nonastigmatic output beams and can be fabricated into high density two dimensional arrays using low-cost batch processing techniques [2]. Additionally, their vertical orientation inherently dictates a short cavity length (∼λ) which causes lasing in a single longitudinal mode. The number of lasing transverse modes, however, is controlled by the device’s lateral dimension. Many applications require single transverse mode emission. The onset of higher order modes at high injection currents can limit the maximum single mode power, and result in a decrease in spatial, and temporal coherence [3]. The origin of these higher order modes is a consequence of the interaction of the spatial distributions of the carriers and the optical field [4]. Specifically, spatial hole burning has been identified as a dominant mode selection mechanism [5].

In short-haul data links, multimode fiber is preferred due to its lower cost, and compatibility with existing links. However, the high coherence of single-transverse-mode VCSEL’s, in combination with the mode selective losses created by fiber optic splitters and connectors, results in modal noise and high bit error rates (BER’s). Large area multimode VCSEL’s have been demonstrated as viable low coherence sources which can reduce modal noise and replace commonly used low bandwidth (<1 GHz) self-pulsating laser diodes and light-emitting diodes [6].

To achieve the needed reliability and low BER’s in these high-speed data links, techniques for characterizing the spectral and spatial properties of multimode VCSEL emission are needed to understand how their complex modal patterns affect system performance.

In this paper, we report the use of near-field scanning optical microscopy (NSOM) for characterizing multitransverse mode proton implanted 850 nm devices used in 2 Gb/s multimode fiber-optic links. Specifically, we have used NSOM to study the spatial and spectral overlap of their transverse modes. We have correlated their measured overlap to oscillations in a spectrally resolved light-versus-current (L–I) curve captured in the far field. Overlapping modes are shown to compete for the available gain while spatially separated modes do not. We show that the high-spatial and high-spectral resolution provided by near-field optical microscopy and spectroscopy makes this an ideal technique for characterizing these low coherence VCSEL’s.

II. THE NEAR-FIELD SCANNING OPTICAL MICROSCOPE

Near-field scanning optical microscopy is a useful tool for characterizing the electrical and optical properties of various semiconductor structures on a nanometer scale [7]. NSOM is a technique in which a tapered optical fiber is held atop a sample within a fraction of a wavelength and scanned across its surface [8]. At each point in the scan, the optical radiation emitted by the sample is collected from the near-field through the small aperture created by the tip of the tapered fiber. The spatial resolution of the scan is determined by the tip size and is approximately equal to the tip diameter (∼100 nm).
The microscope used in this work is shown in Fig. 1. The sample is mounted to a piezoelectric stage, and raster scanned in the $xyz$-plane under the fiber tip, which collects the emission from the sample and guides it directly to a detector to acquire a total intensity measurement or to a spectrometer to obtain localized spectral information. A charge-coupled device (CCD) array cooled by liquid nitrogen is used at the exit of a 0.64 m spectrometer with a 1200-groove/mm grating to yield spectral information with a resolution of 0.07 nm over a 25-nm band for each point of the scan. A commercial scanning probe microscope controller is used for data acquisition.

The tip must track the topography of the sample throughout the raster scan to maintain a fixed tip-to-sample distance of $\sim 10$ nm. This tracking is achieved through simultaneous shear force measurements [9]. A low-cost, nonoptical method of shear-force detection is implemented by mounting the fiber tip onto one leg of the tuning fork of a commercial quartz watch crystal [10]. The fiber tip and tuning fork are dithered by a piezo-electric tube at their resonance frequency, and tip-sample interactions are sensed by the tuning fork as a quenching of this resonance. Monitoring the resonance frequency allows a measurement of the tip-to-sample distance with nanometer resolution. Near-field microscopy thus provides a direct correlation of the emitted optical radiation pattern with topographical features of the sample.

### III. Far-Field Characteristics

The VCSEL devices studied were designed as high-reliability, multimode, gain-guided sources for use in commercial local-area networks (LAN) [11]. The devices were grown by metal-organic chemical vapor deposition (MOCVD) and designed to emit at 850 nm. The structure consists of two AlAs/AlGaAs distributed Bragg reflectors (DBR’s) centered around an active region of GaAs quantum wells to form a $\lambda$ cavity. The devices have a 15-$\mu$m diameter metal ring contact, and a 20 $\mu$m inner diameter, proton-implanted region to confine current. This geometry was chosen to provide the best compromise between threshold current, modulation bandwidth, series resistance, and spectral width [12]. High-speed characteristics, reliability, device, and fabrication details for similar devices can be found in [11]–[13].

The multitransverse-mode nature of these devices is evident in the lasing spectra collected in the far field, and resolved by a spectrometer with 0.07 nm resolution. Fig. 2 shows the far-field spectra at drive currents of 7, 10, 15, and 17 mA. As will be shown in Section IV, the low coherence VCSEL’s in this study do not emit into identifiable mode patterns, but rather into multiple filaments. Consequently, each transverse mode will be identified by its energy. If present, degenerate modes in energy (or, in practice, “almost” degenerate modes) will not be resolved in the spectral data and thus will be lumped together, and designated as one mode. The higher-order modes in confined systems occur at higher energies than the fundamental mode, denoted as mode 0. In a gain-guided VCSEL, lateral confinement is imposed by the spatially nonuniform distribution of the dielectric constant produced by gain guiding, thermally induced index guiding, and carrier-induced antiguiding [4]. In the spectra of Fig. 2, mode 0 occurs at the lowest energy (longest wavelength). At a current (7 mA) just above threshold, two transverse modes are supported with a wavelength separation of $\sim 0.1$ nm. At higher injection currents, additional modes reach threshold. At 17 mA, a total of seven separate transverse modes are observed.

Spatially separated modes in VCSEL’s may theoretically coexist through sharing of the available gain [5]. For transverse modes with significant spatial overlap, modes must compete for the available gain [5]. It is possible to determine the $L-I$ behavior of each resolved transverse mode by fitting each mode of the collected far-field spectra with a Lorentzian line. Taking the ratio of each Lorentzian’s spectral area to the total area, and scaling it to the device’s total optical power yields an $L-I$ curve for each transverse mode.
Fig. 2. Far-field spectra illustrating the device’s multitransverse-mode characteristics for drive currents of 7, 10, 15, and 17 mA.

Fig. 3. Far-field spectrum at 17 mA showing the Lorentzian fits (dotted lines) to each transverse mode of the far-field spectrum at 17 mA. The black dots show the collected data while the solid line shows the sum of all the Lorentzians.

Fig. 4. L–I behavior for each transverse mode illustrating competition or independent coexistence of various modes.

Fig. 5. Representative shear force image acquired during a near-field scan of the topography of the VCSEL’s p-contact. The z-axis is proportional to height and the height difference from the center of the aperture to the top of the contact is ~250 nm.

IV. NEAR-FIELD MEASUREMENTS

A. Shear Force Images

NSOM measurements were taken at drive currents of 7, 10, and 15 mA over a 20 × 20 μm area with 256 × 128 scan points. Several higher resolution images with 512 × 512 pixels were also acquired to study the fine spatial structure observed in some modes. Simultaneously obtained shear force measurements allowed correlation of the optical distributions to the topography of the VCSEL’s top-mirror ring contact. A representative plot of the shear force data acquired during each scan is shown in Fig. 5, with height on the z-axis. The step height from the top of the contact to the center of the aperture is ~250 nm.

B. Intensity Images

Near-field images obtained by guiding the collected light directly into a thermoelectrically cooled germanium detector are shown in Fig. 6. At 7 mA drive current, we resolve two lasing regions with a 10 μm separation located adjacent to the p-contact metal nearest the bond pad in the region of highest current density. The center of the most intense region is near \((X \sim 16 \text{ μm}, Y \sim 14 \text{ μm})\) while a second lower intensity lasing region is at \((X \sim 16 \text{ μm}, Y \sim 4 \text{ μm})\). The nonuniformity of the injected carrier density is apparent. At 10 mA, a third region and the remaining two lasing regions begin to fill along the perimeter of the ring contact. Index guiding through thermal lensing and spatial hole burning are responsible for the formation of a ~2.5 μm radius spot that is centered at \((X \sim 10 \text{ μm}, Y \sim 12 \text{ μm})\), and does not lase. At 2.5 times threshold, additional lasing regions appear, and
the nonlasing spot is reduced to \( \sim 1 \mu m \). The aperture of the VCSEL now appears segmented into more than six smaller filaments of 2–3 \( \mu m \) in diameter.

Fringes are observable in the intensity distributions in Fig. 6. Cross sections of higher resolution scans show that the fringes have a period on the order of half a wavelength. The fringes are not due to scanning artifacts, because they are not aligned with either scan direction and they are also present in the near-field image collected with conventional optics. Clipping of a Gaussian beam by an aperture can impose modulation onto the beam’s intensity profile, however [14]. In these gain-guided devices, the proton-implanted region is larger than the aperture of the p-metal ring contact. Recombination and thus light is present under the metal contact. The difference in the round-trip phase shift experienced by the light under the metal aperture and the light within the clear aperture due to termination of the DBR with metal rather than air creates an effective phase discontinuity which diffracts light. One plausible explanation is that the fringes are high-spatial frequency Fresnel ripples superimposed onto the mode within the near-field as a result of diffraction from this phase aperture. In the measurement plane, the Fresnel number is calculated to be large for micrometer diameter filaments and an assumed effective aperture residing several hundred nanometers below the sample surface. This gives rise to fringes having a period consistent with that observed.

An example of the correlation between the sample’s optical distribution (at 10 mA) and topography is shown in Fig. 7. The shear force data are represented by the rendered three-dimensional (3-D) object. The coloring of the 3-D object represents increasing optical intensity through a color map that progresses from dark blue to purple, to orange, to yellow, to white-cyan. This figure illustrates the location of the three lasing regions relative to the p-contact metal.

C. Spectrally Resolved Images

To obtain spectrally resolved images, the collected light from the NSOM tip was guided to a spectrometer. A total of 32 \( \times \) 32 spectrally resolved scan points were acquired across the aperture. The intensity of each resolvable transverse mode was integrated and its wavelength range false-colored at each scan position. The resulting composite image displays relative intensity and spatial distribution information for each transverse mode. Bilinear interpolation was performed to smooth the pixellated images. An additive color system with red, green, and blue primaries was used for false coloring. Mixing combinations of these primary colors in different proportions creates a spectrum of colors each with a different hue, saturation, and brightness [15]. The colors of the composite image thus relay information on the spatial overlap of the different transverse modes. For reference, if we combine equal proportions of any two primary colors, we get the secondary colors: red and blue create magenta, red and green create yellow, blue and green create cyan, while equal parts of red, green, and blue create white. These secondary colors are the primary colors of the subtractive color system.Overlaying contour lines, created by integrating the total intensity of all the modes, onto this composite image allows comparison of the intensity of one mode to that of another. The contour lines have been colored by an inverted grayscale to be visible on the image. High intensity is represented by dark contour lines.

Fig. 8 shows three composite images for spectrally resolved near-field data at: (a) 7, (b) 10, and (c) 15 mA. A key of the primary colors is shown in the upper-right corner of the images. As shown in Fig. 2, there are two transverse modes (modes 0 and 1) at 7 mA. Mode 0 has been colored with red, and the higher energy mode 1 has been colored with the higher energy false color of green. The strongest mode is mode 0 (red). The most intense portion of mode 0 is at the location \( X \sim 14 \mu m, Y \sim 2.5 \mu m \). The peak intensity of mode 1 (green) is near \( X \sim 12 \mu m, Y \sim 13 \mu m \). As suspected from the competition behavior observed in Fig. 4 for low current, there is spatial overlap between modes 0 and 1 as evident from the orange (reddish-yellow) and yellow-green colors (rather than pure red, and green) in the image.

At 10 mA, three transverse modes coexist. Each mode was again false-colored in order of energy (mode 0 is red, mode 1 is green, and mode 2 is blue), and the composite image is shown in Fig. 8(b). We see several nearly spectrally pure spatial regions of mode 0 (red). Almost all of mode 1 (green) overlaps mode 0, as there is little pure green in the image, but rather yellow. The peak intensity of mode 1 has now migrated to the lobe nearest the contact ring closest to the bonding pad at \( X \sim 14 \mu m, Y \sim 2.5 \mu m \). The contour lines indicate that the majority of the total device power is emitted by the three spectrally pure filaments of the fundamental mode and the large overlapping filament of modes 0 and 1. Mode 2 (blue) has just begun to turn on and begins filling between the stronger modes 0 and 1, with slight overlap.

One limitation of this visualization scheme is the number of transverse modes which can be colored. A maximum of
three modes can be false colored, because there are only three primary colors. At 15 mA, there are four transverse modes. For the image in Fig. 8(c), modes 0 and 1 were false-colored red, while modes 2 and 3 were colored green and blue, respectively. Separate plots (not shown) of the spatial distribution of modes 0 and 1 were used to identify each mode’s contribution to the false color red in the composite image of Fig. 8(c). As indicated in Fig. 4, the most intense lobe of mode 2 (green) appears spatially separated from the other modes near \((X \sim 14 \, \mu m, Y \sim 2.5 \, \mu m)\). A small contribution of mode 1 (red) overlaps with mode 2 (green), creating a yellow tint at the center of the \((X \sim 14 \, \mu m, Y \sim 2.5 \, \mu m)\) location. Significant spatial overlap of modes 1 and 3 is evident by the magenta and pinkish-white colors as well as lack of intense locations of pure blue. These magenta and pinkish-white regions are the most intense lasing filaments. There is one low intensity region of nearly pure white at \((X \sim 6 \, \mu m, Y \sim 9 \, \mu m)\) indicating uniform overlap of all transverse modes.

V. CONCLUSION

Knowledge of the transverse mode characteristics of low coherence VCSEL’s is important in the understanding of system reliability and BER in commercial LAN applications based on these devices. We have studied the transverse mode characteristics of gain-guided multimode VCSEL’s using the high spectral and spatial resolution afforded by near-field scanning optical microscopy and spectroscopy. Far-field spectra were used to calculate light-versus-current behavior for each transverse mode. We have reported the near-field spatial distributions of the emission intensity and lasing wavelengths of the transverse modes. Oscillations in the transverse mode resolved \(L-I\) curves indicated competition for gain among some modes as well as independent coexistence among others. Using the spectrally resolved near-field measurements, we have correlated these oscillations to their spatial overlap. We have experimentally verified that spatially separated transverse modes in VCSEL’s coexist by sharing the available gain, while spatially overlapping modes compete.

We have demonstrated that NSOM is a powerful tool for mapping, and correlating the spectral, spatial, and topographical features of VCSEL’s within the near-field. Unlike bulk-optic techniques which image the lasing aperture through a spectrometer onto a 2-D CCD array, spectrally resolved NSOM has no limitation on spectral resolution imposed by the spatial size of the aperture. We anticipate that further
studies at various heights above the aperture will provide additional information on the angular divergence of the separate lasing filaments. This information will be important in the determination of mode coupling loss and consequently modal noise.

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REFERENCES


Kevin J. Knopp (S’91) received the B.S. degree in electrical engineering from Boston University, Boston, MA, in 1994. He then received the M.S.E.E. degree in optics in 1997 from the University of Colorado at Boulder. He is currently working towards the Ph.D. degree at the University of Colorado.

Throughout his undergraduate studies, he participated in research at both Boston University’s Photonic Research Center and the NASA Langley Research Center (LaRC), Hampton, VA. From 1994 to 1997, he was a recipient of a NASA LaRC Graduate Student Researchers Program fellowship. Since 1997, he has been supported through a National Institute of Standards and Technology (NIST) fellowship, and he has recently been awarded a 1999 National Research Council (NRC) Postdoctoral Associateship to NIST.

His research encompasses the modeling, fabrication, and characterization of vertical-cavity semiconductor devices and a study of their ultrafast photonic properties.

Mr. Knopp is a member of Tau Beta Pi and a student member of the Optical Society of America (OSA).

David H. Christensen received the B.S. degree in physics and mathematics (magna cum laude) in 1980 and the M.S. degree in physics in 1982 from Florida State University, Tallahassee, in 1980 and 1982, respectively, and the M.S. and Ph.D. degrees in electrical and computer engineering from the University of Colorado at Boulder, in 1989.

He is with the Optoelectronics Division at the National Institute of Standards and Technology in Boulder, CO. He is also a Lecturer of physics and Professor Adjunct of electrical and computer engineering at the University of Colorado at Boulder, a National Research Council Postdoctoral Advisor, and Affiliate Professor of materials science and engineering at the University of Washington at Seattle. His present and past publications and research interests include vertical cavity optoelectronics, ultrafast photon and carrier dynamics in semiconductors, in situ monitor and control during molecular beam epitaxy, correlation of destructive and nondestructive ex situ measurements on semiconductors, semiconductor spectroscopy with high-spatial resolution, quantum optoelectronics, optical thin-film physics, mode-locking rare-earth-doped waveguide lasers, and quantum dot physics.

Gerg Vander Rhodes was born on January 15, 1971, in Pittsburgh, PA. He received the B.S. degree in physics from Carnegie-Mellon University, Pittsburgh, PA, in 1993 and the M.A. degree in physics from Boston University, Boston, MA, in 1995. Currently, he is pursuing the Ph.D. degree at Boston University working in the Near-Field Microscopy Laboratory.

His research interests include guided wave devices, photonic bandgap structures, and novel characterization techniques for these, and other photonic devices.

Joshua M. Pomeroy was born on March 10, 1975, in Missoula, MT. He received the B.A. degree in physics with a minor in mathematics from Boston University, Boston, MA, in 1997, where he worked in the Near-Field Microscopy Laboratory for three years.

He is now with Cornell University, Ithaca, NY, where he is working under Prof. B. Cooper in the Energetic Ion Deposition Laboratory. His current research interests include atomic scale manipulation of surface morphology and magnetic multilayer, and spin-valve systems.

Bennett B. Goldberg (M’97) was born in Boston, MA, in 1959. He received the B.A. degree from Harvard College, Cambridge, MA, in 1982 and the M.S. and Ph.D. degrees in physics from Brown University, Providence, RI, in 1984 and 1987, respectively.

Following a Bantrell Postdoctoral appointment at the Massachusetts Institute of Technology, Cambridge, MA, and the Francis Bitter National Magnet Laboratory, he joined the physics faculty at Boston University, Boston, MA, in 1989. He is now an Associate Professor of physics and an Associate Professor of electrical, computer, and systems engineering. His current research interests include low- and room-temperature near-field scanning optical microscopy and spectroscopy in semiconductors and biological systems, magneto optics and magneto transport of low-dimensional electron systems, spectroscopy of wide gap III–V nitrides, and ultrasensitive waveguide biosensors.

Dr. Goldberg is a member of the APS, MRS, and LEOS.

M. Selim Unlu (S’90–M’92–SM’95) was born in Sinop, Turkey, in 1964. He received the B.S. degree in electrical engineering from Middle East Technical University, Ankara, Turkey, in 1986, and the M.S.E.E. and Ph.D. degrees in electrical engineering from the University of Illinois, Urbana-Champaign, in 1988 and 1992, respectively. His dissertation topic dealt with resonant cavity enhanced (RCE) photodetectors and optoelectronic switches.

From 1984 to 1986, he was a part-time Research Engineer with Military Electronics, Inc., Ankara, Turkey, where he worked on VHF communication systems. In 1992, he joined the Department of Electrical and Computer Engineering, Boston University, Boston, MA, as an Assistant Professor and he has been an Associate Professor since 1998. His current research interests include design, fabrication, characterization and modeling of semiconductor optoelectronic devices, near-field and picosecond spectroscopy, integrated optical biosensors, and optical pumping for production of hyperpolarized Xe for MRI.

Dr. Unlu served as the Chair of IEEE Laser and Electro-Optics Society, Boston Chapter in 1994–1995, winning the LEOS Chapter of the Year Award. He was also awarded the United Nations TOKTEN Award in 1995 and 1996 and the NSF-CAREER and the ONR Young Investigator Awards in 1996. He is currently serving as Vice President of the SPIE New England Chapter.