4-2016

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Recommended Citation

CDT Jonathan Dencker, CDT Peter R. Zeidler, CDT David Chacko, William North, Janice Blane, Kirk A. Ingold, Brian Souhan, and James J. Raftery Jr., "Characterization of single-mode vertical cavity surface-emitting lasers," Proceedings of the 2016 National Conference on Undergraduate Research (NCUR), Asheville, NC, (April 2016).

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Proceedings of The National Conference
On Undergraduate Research (NCUR) 2016
University of North Carolina Asheville
Asheville, North Carolina
April 7-9 2016

Characterization of Single-Mode Vertical Cavity Surface-Emitting Lasers

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Abstract

A high-quality single-mode beam is desirable for the efficient use of lasers as light sources for optical data communications and interconnects, however there is little data which characterizes operating ranges and near-field beam qualities of Vertical Cavity Surface Emitting Lasers (VCSELs), which has resulted in a lack of analysis of these devices. Measures of beam quality include beam-quality factor (M^2), Side-Mode-Suppression-Ratio (SMSR) and RMS linewidth. M^2 is a measurement of how closely the beam is to an ideal Gaussian. SMSR is the difference, in dB, between the amplitude of the primary peak and the amplitude of the next highest peak of the output spectrum, with single-mode operation defined by a SMSR > 30 dB. RMS linewidth is a second moment calculation involving the power spectral density, where smaller RMS linewidth indicates higher beam quality. Utilizing a novel vertical M^2 setup in which on-wafer VCSEL M^2 can be measured, a study was conducted on the relation between M^2, SMSR and RMS linewidth, for various oxide-confined VCSELs of varying aperture sizes and Photonic Crystal (PhC) VCSELs of varying aperture sizes and photonic crystal configurations. First, the operating range of the VCSEL was determined utilizing a Semiconductor Parameter Analyzer to obtain the LIV characteristics. Along with this measurement, spectral data was collected using an Optical Spectrum Analyzer at several key operating points, which allowed the RMS linewidths and SMSRs of the devices to be calculated at these points. The novel beam-profiler setup was used to measure the device's M^2. Initial results show a strong correlation between the measures of beam quality, with increasing SMSR, corresponding to M^2 values closer to 1, and single-mode operation characterized by a M^2 of less than 1.5. A strong correlation between RMS linewidth and M^2 was also seen, with increasing RMS linewidths corresponding to an increase in M^2.

Keywords: VCSEL, single-mode, beam quality, M^2, photonic crystal

1. Motivation

Vertical Cavity Surface Emitting Lasers (VCSELs) were first fabricated in 1979 [1]. Since then, VCSELs have been studied and improved to the point that they are now being implemented in commercial applications, predominantly as light sources in short-haul optical communications, such as optical interconnects in data centers [2]. These optical interconnects have largely replaced traditional copper based interconnects because of their substantially higher data rates [3]. VCSELs provide many advantages over their edge-emitting laser (EEL) counterparts, especially in optical communication applications. One of the major drawbacks of EELs is their asymmetric (elliptical) near and far field emission patterns, which reduces the coupling efficiency of these devices into optical fibers [4]. Often times expensive and relatively large corrective lens systems are required to effectively couple the elliptical beam of EELs into circular fiber. Unlike their edge emitting counterparts, VCSELs have a circular emission pattern and a short optical cavity, designed such that the device emits only a single longitudinal mode [5]. Operating optical sources at a single wavelength (i.e. single mode operation) is desirable in optical interconnects and short-haul communications applications because single mode sources exhibit less dispersion than devices operating at multiple wavelengths (i.e.

multi-mode operation), resulting in the ability to transmit data at higher transmission rates and greater distances [5]. Despite only emitting a single longitudinal mode in the direction of propagation, VCSELs have a tendency to operate in multiple transverse modes depending on the width of the oxide aperture [6]. With increasing output power, multiple transverse modes are supported by a cavity because of the two-dimensional extension of the DBRs. This complex transverse modal behavior, occurring at higher pump rates, is generally a major drawback in many applications, particularly optical communication, because the presence of multiple transverse modes decreases the beam quality. For this reason, it is important to be able to measure the beam quality of a device in order to determine the suitability of a device for use in practical applications as well as investigate design parameters and operating characteristics of VCSELs in order to optimize their performance in optical communications applications.

2. Background

VCSELs are semiconductor lasers, epitaxially grown on the surface of a semiconductor substrate, typically GaAs. The structure is comprised of a cavity consisting of a multiple quantum well active region, typically one wavelength long so that the device emits only a single longitudinal mode. Positively and negatively doped Distributed Bragg Reflectors (DBRs) enclose this cavity. Each DBR is a quarter-wavelength thick structure consisting of grated layers of materials with varying indexes of refraction, making it extremely (up to 99 percent) reflective [7]. The DBRs are designed such that the waves that reflect off of them interfere constructively with one another, further increasing the efficiency of the resonator [7]. The p-DBR and n-DBR form the double heterostructure typically found in semiconductor lasers where the top, or p-DBR, is designed to be slightly less reflective in order for light to be transmitted (output) through this region.

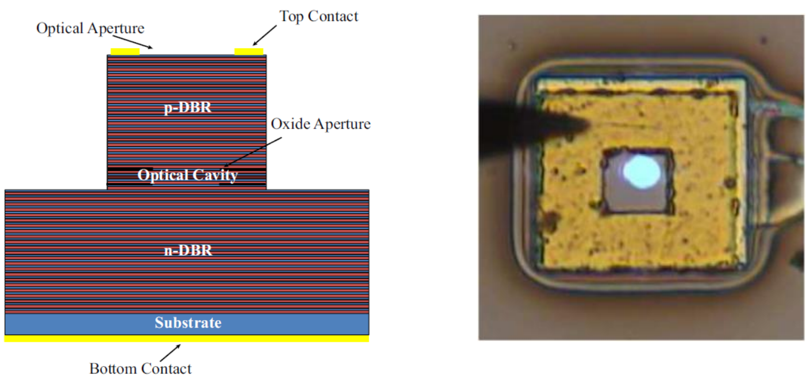
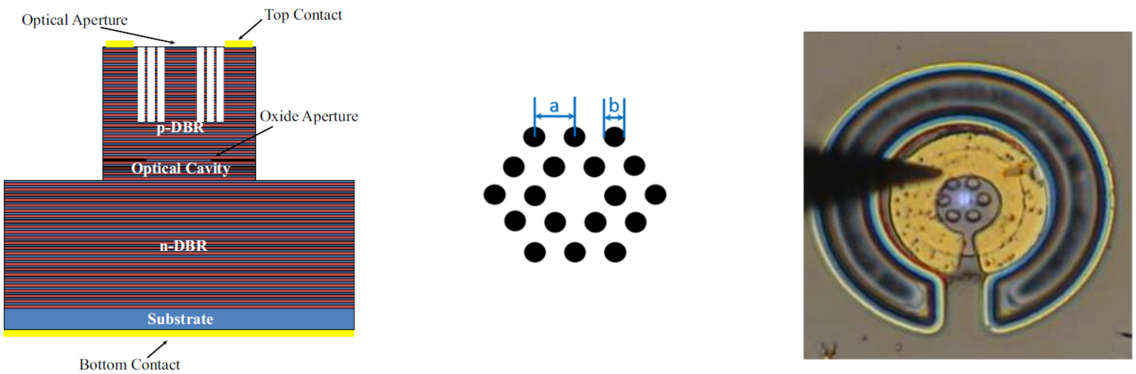


Figure 1. Oxide-confined VCSEL (Left) structure (Right) near-field image

Current is injected into the top gold (Au) contact located above the p-DBR region. The current travels through the p-DBR region, is confined by the oxide aperture to the gain medium consisting of a multiple quantum well. It is in this region that photons are primarily generated. The current then travels to the n-DBR region and finally through the GaAs substrate to the bottom contact, completing the circuit. The threshold current, the current at which lasing occurs, and the rollover current, the current at which peak light output occurs, are both directly related to the volume of the active region. In general, decreasing the diameter of the active region will result in lower threshold currents [1] and higher beam quality, but comes at the cost of lower power outputs [8]. This power limitation has prompted further research into fabrication techniques that would allow for higher power outputs at lower threshold currents in order to maximize efficiency.

Although there are several different methods for confining current, it has been demonstrated in [9] that oxide-confined devices exhibit the best performance in terms of threshold currents and power efficiency. For these reasons, oxide-confined devices are the most commonly used VCSELs in commercial applications [5]. Because VCSELs have a tendency to operate in multiple transverse modes depending on the width of the oxide aperture [9] and the amount of injected current [5], additional research into new fabrication techniques seeking to maximize power output at smaller aperture sizes, and thus lower threshold currents, has resulted in the Photonic Crystal (PhC) VCSEL.

PhC VCSELs are oxide-confined VCSELs that have undergone an additional fabrication process known as photonic crystal implantation. In these devices, a two-dimensional periodic pattern of holes, defined by a b/a ratio, is etched into the top or p-DBR as can be seen in Fig. 2. The b/a ratio is the ratio of the diameter of the etched holes, defined as b, and the distance between the centers of the etched holes, defined in [10]. The difference in the index of refraction between the etched space and the un-etched material confines the optical power to a single transverse mode by acting as a waveguide that supports only the lowest order mode [6]. This study characterized the operation of both oxide-confined and PhC VCSELs of varying b/a ratios and etch depths (as measured by etch time) with similar aperture sizes in order to determine if the PhC implantation improved the performance of a device.



(a) (b) (c)

Figure 2. PhC VCSELs (a) Structure. (b) b/a ratio. (c) Near-field image of PhC VCSEL in operation.

Traditionally, the performance of a single-mode VCSEL has been determined by its side-mode suppression ratio (SMSR), which is a measurement taken from the power spectral density of the beam. Specifically SMSR is the difference in the peak of the fundamental mode and the next highest peak in the power output spectrum. A single-mode device is defined by a SMSR > 30 dB in [9].

A second measure of beam quality used to quantify the beam quality of VCSELs is power root-mean-square (RMS) linewidth, which is used to measure the spectral width of the beam. The spectral width of a beam is an especially useful measurement of beam quality for VCSELs because VCSELs tend to emit multiple transverse modes [6]. When fewer transverse modes are being emitted, the spectral width of the beam will be smaller, resulting in less chromatic and modal dispersion [11, 12]. RMS linewidth is a second moment calculation given by equation (1) [13]:

$$\sigma_\lambda^2 = \frac{\int_{-\infty}^{\infty} (\lambda - \bar{\lambda})^2 |f(\lambda)|^2 \, d\lambda}{\int_{-\infty}^{\infty} |f(\lambda)|^2 \, d\lambda}, \text{ where } \bar{\lambda} = \frac{\int_{-\infty}^{\infty} \lambda \, |f(\lambda)|^2 \, d\lambda}{\int_{-\infty}^{\infty} |f(\lambda)|^2 \, d\lambda} \tag{1}$$

where $|f(\lambda)|^2$ is the power spectral density function, from which the calculation is made. λ is the wavelength and $\bar{\lambda}$ is the mean wavelength.

The beam quality factor measurement, or M^2 measurement is a measurement of how close to Gaussian the beam's intensity distribution is [13]. An ideal beam, with ideal beam quality, would be perfectly Gaussian and thus have an M^2 of 1. As the distribution becomes less Gaussian, beam quality decreases, and the M^2 value increases. For a given wavelength, the M^2 value is dependent on both the beam width and divergence of the beam in the direction of propagation [14]. Initial research reveals that M^2, or beam quality factor measurements, is one of, if not the least measured characteristic of VCSELs. In order to take M^2 measurements, a novel M^2 measurement setup was developed in the Photonics Research Center at West Point. This allowed the beam quality characteristics of both PhC and oxide-confined VCSELs to be measured in order to observe the effects of PhC implantation and to attempt to correlate M^2, with the other measures of beam quality, SMSR and RMS linewidth.

3. Experimental Setup

The setup was designed to take vertical M^2 measurements as shown in Fig. 3 below [5]. A Thorlabs BP106-VIS CCD Camera Beam Profiler and BP1M2-150 Profiler Extension Set, equipment designed to profile beams in a

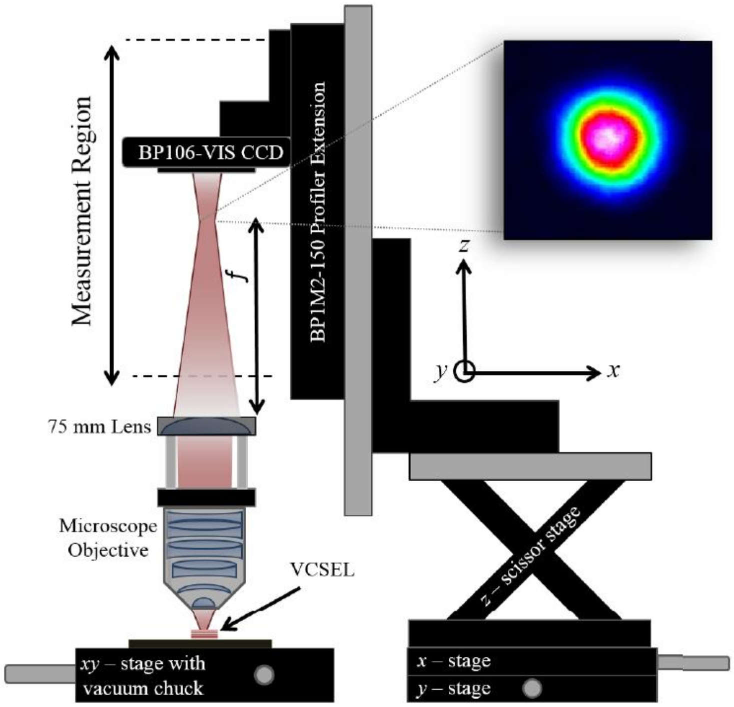


Figure 3. Novel M^2 Setup

horizontal plane, was mounted vertically in a configuration that allowed for the measure of the beam profiles of on-wafer VCSELs. The International Standards Organization (ISO) has a defined standard, ISO 11146, for the proper way to take M^2 measurements [15]. ISO 11146 calls for at least 5 measurements within the Rayleigh Range on either side of the beam waist, and at least 5 measurements outside two Rayleigh Lengths from the beam waist, as depicted in Fig. 4 below [16]

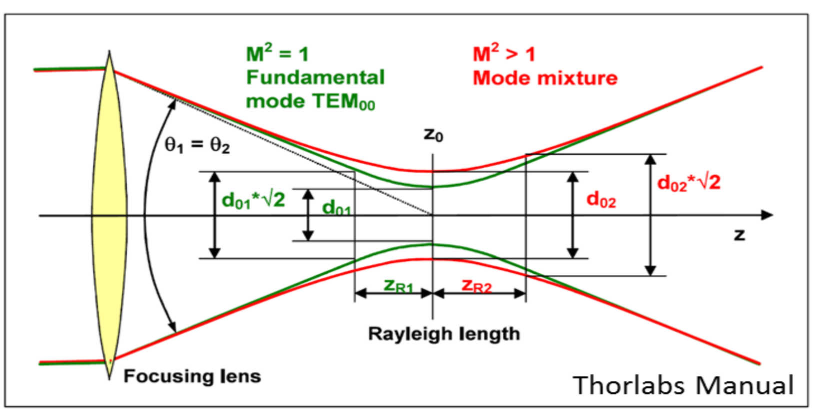


Figure 4. Diagram depicting M^2 measurement regions [16].

As seen in the setup depicted in Fig. 3, the VCSEL is held to the grounded stage with a vacuum chuck in order to ensure the current has a path to ground. The light output from the VCSEL is then passed through a Mitutoyo 50x infinity-corrected long working distance objective which is used to collimate the beam. The collimated beam is then passed through a 75 mm lens which was chosen to focus the beam at the midpoint of the 150 mm profiler extension set, allowing for adequate measurements to be taken on both sides of the beam waist to meet the ISO standard.

The light-current-voltage (LIV) characteristics of each device was measured with a Semiconductor Parameter Analyzer (SPA). By varying the injected current, with a resolution of 20 μA, and measuring the resultant voltage and light output, an LIV curve can be generated. From these measurements, it is possible to obtain the threshold current, the current at which lasing occurs, and the thermal rollover current, the current at which maximum light output occurs. Knowing these currents allows the device's operating range to be determined. VCSELs can be operated anywhere along this operating range, unlike EELs which must be operated at their maximum power output [17]. It is then possible to take spectral measurements at key points along this operating range, such as the midpoint current, which is the mid-point of the rollover and threshold currents. Spectral measurements are taken at this point because it is within the linear region of the VCSEL operating range. The power spectral density was measured using an Optical Spectrum Analyzer (OSA), from which the RMS linewidth and SMSR of the device was calculated.

The results of this paper include measurements of both oxide-confined and PhC VCSELs with a wavelength of 850 nm. The oxide-confined VCSELs of aperture sizes 2.5 μm and 5 μm were compared with PhC VCSELs with 5 μm apertures, etch times of 6 and 8 minutes, and b/a ratios of 0.6 and 0.7.

4. Results

After measuring the SMSR, RMS linewidth, and M^2 of oxide-confined devices, with 2.5 μm and 5 μm apertures across their operating ranges, the following data was analyzed. In Fig. 5 below, M^2 measurements are compared with SMSRs and RMS linewidths along the operating range of both the 2.5 μm and 5 μm devices.

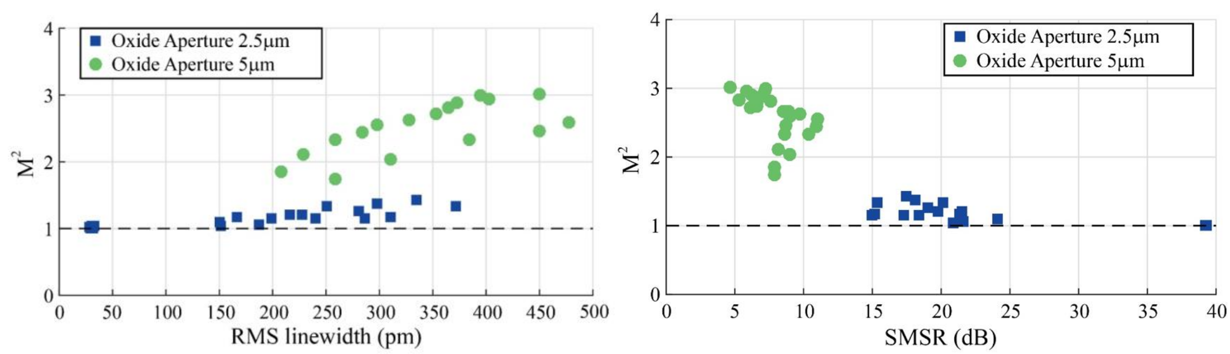


Figure 5. Oxide-confined measurements (Left) M^2 vs. RMS linewidth (Right) M^2 vs. SMSR

It can be seen that there is a general correlation between M^2, SMSR and RMS linewidth, namely as RMS linewidth increases, so does M^2, and as SMSR increases, M^2 decreases. Additionally, smaller aperture devices exhibit M^2 measurements closer to one. It is clear from Fig. 5 that there is a distinct difference between the devices, in terms of SMSR. None of the 5 μm devices exhibited an M^2 less than 1.6 or an SMSR greater than 12 dB. Each of the 2.5 μm devices exhibited an M^2 less than 1.5 and an SMSR greater than 15 dB; however, the measured 15 dB SMSR for the 2.5 μm devices was limited by the noise floor on the OSA, preventing a true measurement of the SMSR. These ranges are important because the 2.5 μm aperture devices operated in single mode, whereas the 5 μm aperture devices operated in multi-mode. The relation of M^2 as a third measure of beam quality allows this distinction to be made because there is a clear distinction between the M^2 values of the single and multimode devices, which occurs at an M^2 of approximately 1.5.

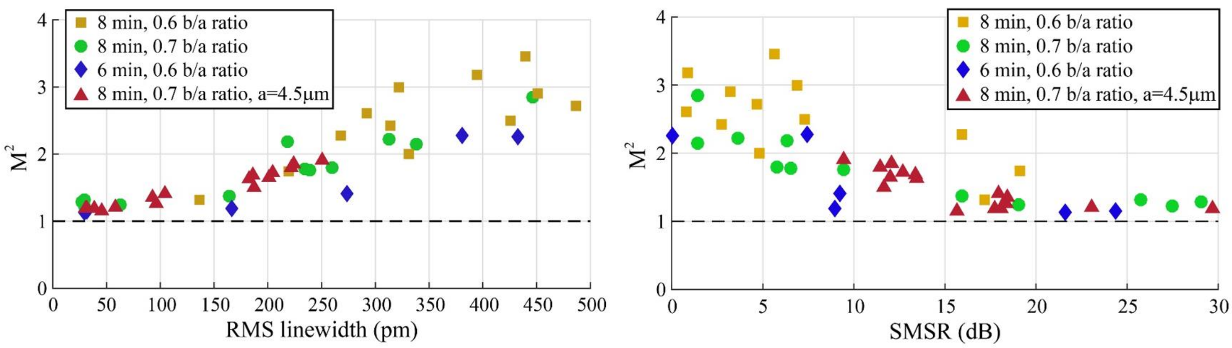


Figure 6. PhC VCSEL measurements (Left) M^2 vs. RMS linewidth (Right) M^2 vs. SMSR

Fig. 6 compares the M^2 values of PhC VCSELs, with 5 µm apertures, and varying etch depths and b/a ratios, with their SMSRs and RMS linewidths. It can be seen from Fig. 6 that the same general trend occurs between the three measurements of beam quality, further validating M^2 as a viable and useful measure of beam quality. It is clear that b/a ratio has an impact on the beam quality as each of the PhC devices have a 5 µm aperture, yet they have beam qualities that span the same range that the oxide-confined VCSELs did, as can be seen in Fig. 7. This shows that at a

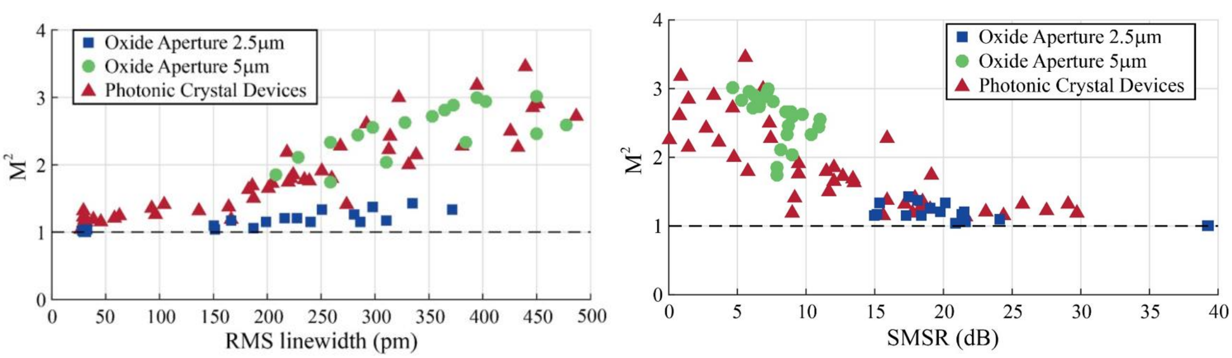


Figure 7. PhC and Oxide-confined VCSEL measurements (Left) M^2 vs. RMS linewidth (Right) M^2 vs. SMSR

given aperture size, by using PhC implantation, it is possible to increase the beam quality with the proper b/a ratio. When the measurements from both the PhC VCSELs and the oxide-confined VCSELs are overlaid, the relationship between M^2, SMSR and RMS linewidth becomes more apparent.

In general, the data shows that it is useful to incorporate M^2 as a suitable measure of beam quality, along with SMSR and RMS linewidth. This study suggests that single mode operation could be defined by an $M^2 < 1.5$.

5. Future Work

In the future, a more in-depth parametric study of a single device over its entire operating range would be appropriate to conduct, in the hopes of expanding on the initial conclusions presented above. In the research described in this paper, measurements were taken at key points along the operating range, such as light output mid-point, and compared with measurements taken at the same point from other devices. It would be interesting to look at how operating a device along its entire operating range affects the beam quality and efficiency of the device. Additionally, the M^2 setup can be improved by incorporating M^2 measurements on multiple axes instead of just along the x and y-axis. Another way to improve the M^2 measuring setup would be to create a method for isolating the individual modes of a multi-mode device in order to obtain the M^2 of each individual mode. Both of these improvements can be easily implemented without any additional hardware, but merely by programming the current equipment differently. Future work in these areas will be conducted using similar devices from the ones in this research.

6. Acknowledgements

This research was conducted in the Photonics Research Center at the United States Military Academy in collaboration with 2LT Peter Zeidler and supported by the efforts of 2LT David Chacko, CPT William North and CPT Janice Blane. This research would not have been possible without the help and guidance of advisors LTC Kirk Ingold, LTC Brian Souhan, and COL James Rafferty, Jr. or funding from Army Research Laboratory. The devices were fabricated and provided by Professor K. D. Choquette at the University of Illinois-Urbana-Campaign.

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