PHOTONICS TECHNOLOGY DEVELOPMENT FOR OPTICAL FUZING

Christian M. von der Lippe*
U.S. Army Armament Research Development and Engineering Center
AMSRD-AAR-AEP-F(A), Adelphi, MD 20783

G. A. Keeler, D. K. Serkland, K. M. Geib, G. M. Peake, and A. Mar
Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185

J. Jiang Liu
U.S. Army Research Laboratory, AMSRD-ARL-SE-EM, Adelphi, MD 20783

ABSTRACT

This paper describes the photonic component development, which exploits pioneering work and unique expertise at Sandia National Laboratories, ARDEC and the Army Research Laboratory by combining key optoelectronic technologies to design and demonstrate components for this fuzing application. The technologies under investigation for the optical fuze design covered in this paper are vertical cavity surface emitting lasers (VECSELs), integrated resonant cavity photodetectors (RCPD), and diffractive micro-optics. The culmination of this work will be low cost, robust, fully integrated, g-hardened components designed suitable for proximity fuzing applications. The use of advanced photonic components will enable replacement of costly assemblies that employ discrete lasers, photodetectors, and bulk optics. The integrated devices will be mass produced and impart huge savings for a variety of Army applications.

1. INTRODUCTION

Optical Fuzing (OF) is a promising alternative approach to standoff fuzing traditionally using RF or RADAR proximity fuzes. The OF sensing techniques are ideal in situations where a highly directional sensor is called for. Development in photonic component technology allows OF becoming a cost effective solution for application in precision weapons for the Future Combat System ordinance. The inherent directivity of laser emission provides a means of actively sensing targets in cluttered environments. This capability is ideal for direct fire and flat fire munitions. Development of OF technology fills a gap that exists currently in the fuzing area. The advancement of the photonic component technology can provide the foundation for low cost precision fuzing for both short and long standoff sensing [Ruff, *et al*. 1994; Stann, *et al*. 1996]. Figure 1 shows a typical implementation of an OF for a gun-fired projectile.

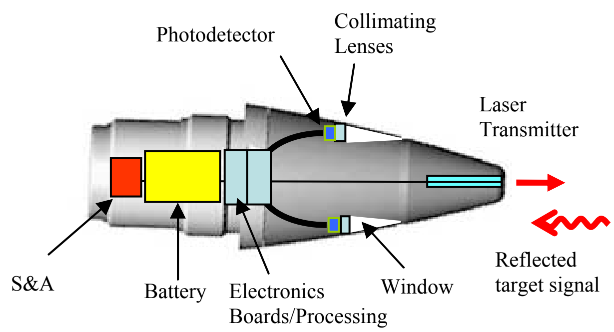

Fig. 1. Illustration of an Optical Fuze for a gun-fired projectile.

Our goal is to develop a gun-fired compact photonic proximity sensor for munition applications. The photonic component development takes advantage of emerging technology by combining key optoelectronic technologies to design and demonstrate components for this fuzing application. The technologies under investigation in the optical fuze design are vertical external-cavity surface-emitting laser (VECSEL), integrated resonant cavity photodetectors (RCPD), and diffractive micro-optics. This work will culminate in a robust, fully integrated, g-hardened component design suitable for proximity fuzing applications. Costly assemblies that employ discrete lasers, photodetectors, and bulk optics will be replaced in the sensors to be mass manufactured. Development of these parts will produce significant savings. The specific application under investigation is for gun-fired munitions. Nevertheless, numerous civilian uses exist for this proximity sensor in automotive, robotics and aerospace applications.

In order to realize integrated components, combination of lasers and photodetectors requires careful balance of design constraints. There are different criteria for designing optoelectronic devices to emit light versus

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **00 DEC 2004**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Photonics Technology Development For Optical Fuzing**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Armament Research Development and Engineering Center AMSRD-AAR-AEP-F(A), Adelphi, MD 20783; Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES **See also ADM001736, Proceedings for the Army Science Conference (24th) Held on 29 November - 2 December 2005 in Orlando, Florida. , The original document contains color images.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**5**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

absorption of light. The requirements on the laser epitaxial design are clearly more stringent. Finally, the micro lenses to be used in the sensor may need to be fabricated in a different material than GaAs used for lasers and photodetectors because the substrates become prohibitively absorptive at wavelengths shorter than or close to the band-edge energy. This necessitates fabrication of the micro lenses in fused silica that would be compatible across the visible and near infrared spectrum.

2. HIGH-POWER VECSEL

For the optical fuze, an advanced high power vertical-external-cavity surface-emitting laser (VECSEL) is employed as the optical transmitter source. VECSEL combines the advantages of high output power of an edge-emitting laser with the superior beam quality of a standard VCSEL [Alford, *et al*, 2002]. The material structure of a VECSEL was grown by metal-organic chemical vapor deposition (MOCVD) on a low-doped *n*-type GaAs substrate. The first epitaxially-grown mirror, which acts as a partial reflector in the laser cavity, consists of an *n*-type GaAs/AlGaAs distributed Bragg reflector (DBR) with eight periods. It is followed by a three-quantum-well InGaAs active region (with λ_{gain}~965 nm) and a 36-period *p*type GaAs/AlGaAs high reflector to form a cavity whose resonance wavelength is at about 970 nm.

The VECSEL mesas were first etched on the epitaxal structure followed by depositing top-side anode and cathode metal contacts. An electrical current aperture was created by proton implantation. The diameter of the current aperture is approximately 28 μm in this research. Next, the GaAs wafer was lapped and polished to a thickness of 70 μm and a silicon nitride anti-reflection (AR) coating was applied. After flip-chip bonding the device arrays to an aluminum nitride heatsink, the indium bumps that cover the VECSEL mesas provide a high-conductivity path for heat dissipation. Coplanar gold traces on the heatsink enable electrical contact to the lasers. A VECSEL structure with a coupled external-cavity design is shown in Fig. 2.

3. MICROMIRROR OF VECSEL

A concave external mirror provided the optical confinement needed to support a large-diameter (>20 micron) low-loss optical mode that extracts power from a relatively large active area. Previously investigated designs have employed a bulk-optics mirror to form the external cavity, so every device required separate alignment and testing. By incorporating an integrated micromirror, we demonstrated a compact device that can be fabricated using a wafer-scale process.

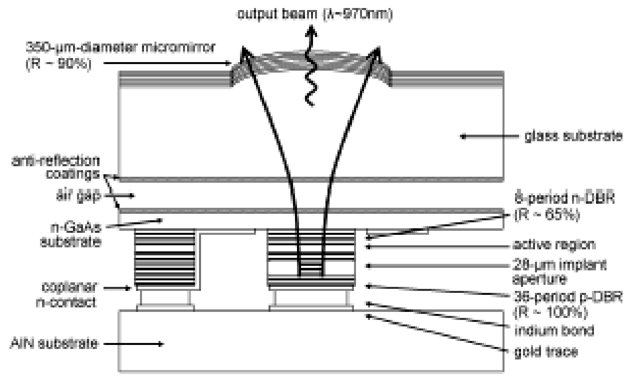

Fig. 2. Schematic view of the VECSEL. The thin, AR-coated semiconductor substrate was used (~70 μm) to improve current spreading at the expense of intra-cavity losses. The glass substrate backside was also AR-coated to prevent reflections.

The passive micro-optic portion of the device consists of a glass substrate with a curved micromirror that acts as the output coupler. The micromirror is formed by depositing a SiO_2/Si_3N_4 DBR stack onto a transparent convex microlens, resulting in a reflectivity of 90%. The micromirror is actively aligned to the VECSEL aperture and a thin air gap is retained between the glass and semiconductor substrates to facilitate alignment. Thus, the backside of the glass substrate is also AR-coated to prevent intra-cavity reflections. Several methods exist to fabricate microlenses and to transfer their shape into appropriate substrates, but the vast majority of techniques produce small *ROC* lenses that are unsuitable in this application. Thermal reflow of photoresist cylinders is useful for moderately large *ROC* microlenses, but to achieve the required lens thickness (i.e., only a few microns) for such a large lens diameter, we have performed the reflow process in a heated acetone atmosphere. Using the acetone vapor prevents premature hardening of the photoresist (Hoechst AZ5214) during the reflow process and achieves the smooth surface expected from thermal reflow. The mold was used to form replicas of the microlens arrays on a glass substrate in a thin layer of high-temperature optical epoxy, Tra-Bond F202 [Houlihan, *et al*, 2002].

Fig. 3 shows a three dimensional interferometric image of a microlens before DBR deposition. The 350-μm-diameter lenses have a radius of curvature of approximately 2.4 mm, and atomic force microscopy measurements yield an rms surface roughness of only a few nanometers. Deposition of the dielectric DBR by plasma-enhanced chemical vapor deposition (PECVD) completes the micromirror fabrication process.

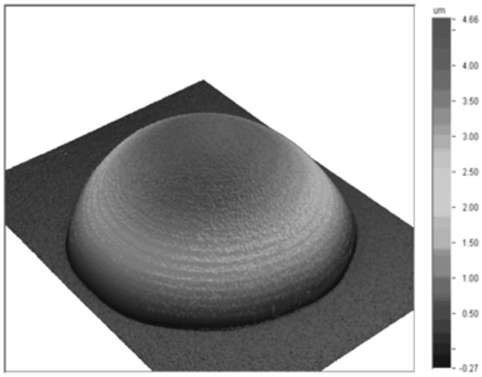

Fig. 3. Surface profile of a micromirror (convex side). Lens diameter is 400 μm and lens height ~4.5 μm.

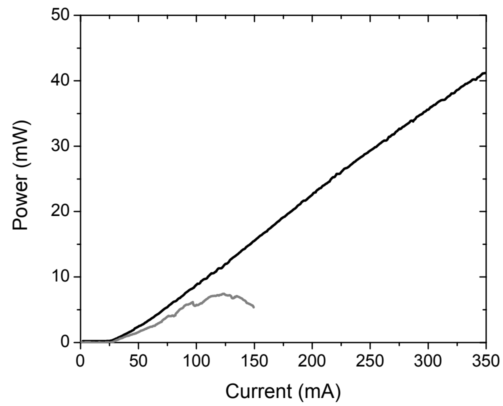

Fig. 4. The output power versus current for a 28-micron aperture VECSEL operating under cw (saturated at 125 mA) and pulsed modes (1 μs pulses with 1% duty cycle).

The curved micromirrors were designed to have a large radius of curvature and minimal surface roughness. These characteristics were achieved by reflowing photoresist pillars on a silicon substrate using a solvent vapor. To preserve the quality of the optical surface, standard pattern-transfer etching methods were avoided. Instead, a silicone mold of the master was formed, and an optical epoxy with high temperature resistance was used to create transparent replicas on glass. Finally, a SiO_2/Si_xN_y DBR was deposited, yielding arrays of micromirrors with the appropriate curvature and smoothness.

4. CHARACTERISTICS OF THE INTEGRATED VECSEL

We fabricated VECSELs with several aperture sizes and characterized them at room temperature. Fig. 4 shows the output power and voltage versus current for a 28-micron aperture laser using pulsed drive to illustrate its characteristic parameters. A threshold current of 25 mA and a slope efficiency of roughly 12% were typical for devices with this aperture size, which achieved higher output power than other devices under continuous-wave (cw) operation, the laser output power is limited to about 10 mW before thermal rollover occurs. Complete removal of the GaAs substrate should significantly increase output powers by reducing below-band-edge optical absorption in the GaAs substrate.

The pulsed measurement shown in Fig. 4 indicates the significance of heating. Improved heat extraction and gain wavelength offset are being pursued. The slope efficiency is limited to ~10.5% because of high intracavity losses, an exceedingly high reflectivity output coupler (R~97%), and mismatch between the spatial gain profile and the optical mode.

Tests on high frequency modulation showed a 3-dB fall-off bandwidth of approximately 900 MHz on these micromirrored VECSELs. Analyses showed that a total capacitance of 4 pF existed for this integrated structure (1 pF on the device and 3 pF from the packaging parasitic). Such a limitation can be improved by thinning the conductive substrate and making better device packages.

5. INTEGRATED RCPD

RCPDs are attractive for the fuze application since the device uses the same epitaxial material as the VECSEL for ease of integration. They also have high wavelength sensitivity and a correspondingly high peak responsivity to enhance immunity to background and countermeasures; the wavelength tracks with VECSEL due to both being on same die substrate.

The VECSEL and RCPD epitaxial structures are the same except for device cross-sectional area of the etched mesas. The epitaxial n-side mirror is of appropriate reflectivity for good RCPD operation, (lower R than required for lasing). In the case of 980nm RCPDs, the n-side mirror has only 8 mirror pairs. The AR coating on the micromirror over the VECSEL device provides additional optical feedback for achieving lasing while the mirror curvature provides selectivity for a low-divergence optical mode. The microlens collection optic is optimally AR coated for detector operation. In this way the RCPD devices are integrated/differentiated with the VECSEL sources. Figure 5 shows a monolithically integrated VECSEL and RCPD structure. The integrated VECSEL and RCPD structure was flip-chip bonded onto a AlN heat-sinking substrate. The electrical contacts were underfilled to insure good electrical current flow.

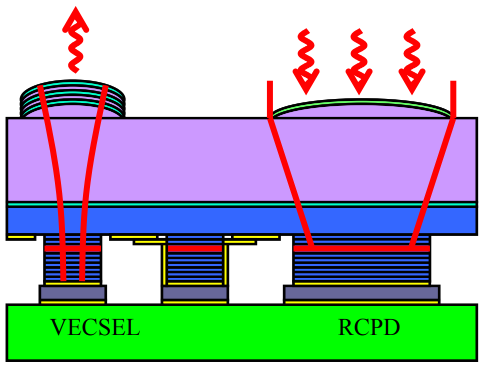

Fig. 5. Cross-sectional view of a monolithically integrated VECSEL and RCPD structure. Transmission and reception of laser light are also illustrated.

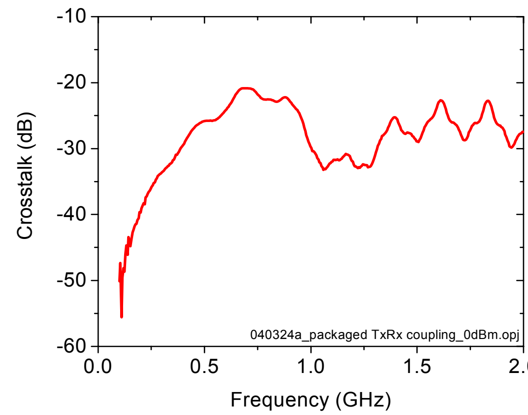

Fig. 7. Electrical cross-talk of the integrated VECSEL and RCPD structure versus the operation frequency.

Initial tests were carried out on the RCPD. The RCPD was characterized for its optical responsivity around the region of 980 nm laser output wavelength. A maximum responsivity of ~0.3 A/W was measured at 970nm for the RCPD with 8-period DBR. The wavelength response of this RCPD was found to be about 10 nm on full-width at half-maximum (FWHM), as shown Figure 6.

Operation on this monolithically integrated system was performed using neighboring VECSEL and RCPD. The laser output from the VECSEL was transmitted through a large area lens, reflected back by a mirror, and then focused back to the RCPD through the same large lens. VECSEL was electrically modulated using external pattern generator. The received signal on the RCPD was terminated with 50 ohms and displayed on an oscilloscope. The transmission and receiving on this integrated system was successful demonstrated at 500 MHz so far.

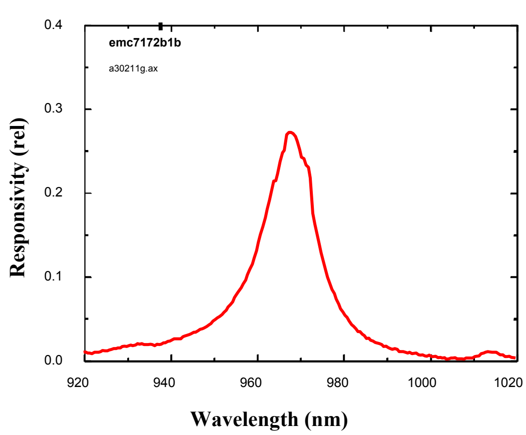

Fig. 6. Opical responsivity and wavelength bandwidth of a RCPD with 8-period DBR.

The cross-talk of this system was also investigated. Electrical cross-talk due to the conductive substrate was found to be about -30dB under the operation frequency of 0.5 GHz. The behavior of the electrical cross-talk is shown in Figure 7. Such capacitive coupling caused behavior can be improved by reducing wire inductance to the on-chip ground and using individual electrical contacts instead of common ones.

5. SUMMARY

Even though the adaptation of this photonic component technology for fuzing needs is in its infancy, progress is being made towards completely integrated systems. Advancement of photonic component technology is critical to making low cost optical fuzing a reality. The work under investigation will benefit from high power, high bandwidth VCSELs and low noise high sensitivity detectors. Given the limited space and significant power constraints for the fuzing application, it is essential to maximize detector performance and increase transmitter efficiency. Ultimately, integration of the various devices would reduce size and simplify the fabrication process. The photonics component work is critical to making a low cost, mass manufacturable and gun-hardened optical proximity fuze for Army needs.

REFERENCES

W. C. Ruff, B. L. Stann, Christian M. von der Lippe, “Ladar Sensor Candidates for a Short Standoff Fuze”, *ARL report*, (May 19, 1994).

B. L. Stann, W. C. Ruff, and Z. G. Sztankay, "Intensity-modulated diode laser radar using frequency-modulation/continuous-wave ranging techniques", Opt. Eng., Vol. 35, No. 11, pp.3270-3278 (Nov. 1996).

W. J. Alford, T. D. Raymond, and A. A. Allerman, "High power and good beam quality at 980 nm from a vertical external-cavity surface-emitting laser", *J. Opt. Soc. Am*. B, Vol. 19, pp. 663-666 (2002).

F. Houlihan, M. Kunnavakham, A. Liddle, P. Mirau, O. Nalamasu, and J. Rogers, "Microlens arrays for optoelectronic device", J. Photopolym. Sci. Tchnol., Vol. 15, pp. 497-515 (2002).