AFRL-SN-RS-TR-1998-72
Final Technical Report
May 1998

1:N SPACE DIVISION SWITCHES FOR OPTICAL ROUTING, RECONFIGURABLE INTERCONNECTIONS, AND TIME AND WAVELENGTH-DIVISION SWITCHING APPLICATIONS

Cornell University

D. B. Shire and C. L. Tang

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

AIR FORCE RESEARCH LABORATORY
SENSORS DIRECTORATE
ROME RESEARCH SITE
ROME, NEW YORK

This report has been reviewed by the Air Force Research Laboratory, Information Directorate, Public Affairs Office (IFOIPA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the general public, including foreign nations.

AFRL-SN-RS-TR-1998-72 has been reviewed and is approved for publication.

APPROVED: Michael A Parker

MICHAEL A. PARKER
Project Engineer

FOR THE DIRECTOR: Robert G. Polce

ROBERT G. POLCE, Acting Chief
Rome Operations Office
Sensors Directorate

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
May 1998

3. REPORT TYPE AND DATES COVERED
Final Jun 96 - Sep 97

4. TITLE AND SUBTITLE
1:N SPACE DIVISION SWITCHES FOR OPTICAL ROUTING, RECONFIGURABLE INTERCONNECTIONS, AND TIME AND WAVELENGTH-DIVISION SWITCHING APPLICATIONS

5. FUNDING NUMBERS
C - F30602-96-C-0042
PE - 62702F
PR - 4600
TA - P5
WU - PB

6. AUTHOR(S)
D. B. Shire and C. L. Tang

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Cornell University
Office of Sponsored Programs
120 Day Hall
Ithaca NY 14853-5401

8. PERFORMING ORGANIZATION REPORT NUMBER
N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFRL/SNDP
25 Electronic Pky
Rome NY 13441-4515

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
AFRL-SN-RS-TR-1998-72

11. SUPPLEMENTARY NOTES
AFRL Project Engineer: Michael A. Parker/SNDP/(315) 330-4918

12a. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

We report the first observation of two-mode intensity bistability in intracavity-coupled in-plane lasers and oxide-confined vertical-cavity surface emitting lasers (VCSELs) operating under room-temperature continuous wave (CW) conditions. These devices have been integrated in a monolithic all-optical 1xN routing switch. The VCSEL sections act as output couplers for modulation signals introduced to the main ridge-waveguide in-plane laser or the side in-plane control lasers, and the combined devices are capable of time-division multiplexing and demultiplexing operations. Hysteresis in the input-output transfer characteristics of the coupled in-plane lasers and VCSELs also leads to bistable operation over a range of bias conditions. The on/off contrast ratio is >29 dB, and there is negligible crosstalk between the output channels. These devices have a wide variety of potential applications, including logic gates and data buffers in optical switching networks.

14. SUBJECT TERMS
Vertical-cavity surface emitting lasers (VCSELs), laser quenching, optical logic

15. NUMBER OF PAGES
20

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Table Of Contents

Acknowledgments

The authors wish to acknowledge the valuable technical collaboration with Dr. Michael Parker of the Rome Laboratory Photonics Center on this research program, and technical discussions and training from S. Pesarcik and the staff of the Cornell Nanofabrication Facility. C. Lei and L. Hodge of Hewlett-Packard Company's Components Group supplied some of the epitaxial material used in the fabrication of the devices discussed here, and J. L. Rossi of Rome Laboratory was also of valuable assistance with administration of this work.

Executive Summary

We report the first observation of two-mode intensity bistability in intracavity-coupled in-plane lasers and oxide-confined vertical-cavity surface emitting lasers (VCSELs) operating under room-temperature CW conditions. These devices have been integrated in a monolithic all-optical 1xN routing switch. The VCSEL sections act as output couplers for modulation signals introduced to the main ridge-waveguide in-plane laser or the side in-plane control lasers, and the combined devices are capable of time-division multiplexing and demultiplexing operations. Hysteresis in the input/output transfer characteristics of the coupled in-plane lasers and VCSELs also leads to bistable operation over a range of bias conditions. The on/off contrast ratio is >20 dB, and there is negligible crosstalk between the output channels. These devices have a wide variety of potential applications, including logic gates and data buffers in optical switching networks.

Bistable Operation of Coupled In-Plane and Oxide-Confined Vertical-Cavity Laser 1xN Routing Switches

We report the first experimental demonstration of bistable operation in intracavity-coupled in-plane lasers and oxide-confined VCSELs. This effect is demonstrated in a monolithically-integrated all-optical 1 x N routing switch which operates CW at room temperature. It has been shown both theoretically and experimentally that intracavity-coupled lasers can exhibit complete gain quenching of the stimulated emission in the controlled device, as well as bistability in their input-output characteristic[1-6]. These coupled lasers can be fabricated in any number of combinations in order to achieve the desired logic, routing, or memory functions. For example, Shire et al. have demonstrated a NOR gate based on mode competition in a shared laser gain region[2], and Johnson et al. demonstrated an all-optical flip-flop based on the same principle[4]. This work is distinct from bistable switching laser designs which have employed saturable absorber sections in a main laser which are then controlled by injecting side light into the absorber(s). In this case, the gain region common to the intersecting in-plane lasers is the VCSEL output device itself, which is independently biased. In addition to serving as a large-aperture output coupler for the modulation signal from the main in-plane laser, the VCSEL facilitates signal transmission via free space or optical fibers by virtue of its low-divergence output beam.

The bistability we observe may be used for optical memory purposes or for digital optical signal regeneration due to the combined laser device's thresholding capability. Furthermore, the waveform regeneration and reshaping properties and the concomitant improvement in the bit error rate of degraded optical inputs (such as clock signals) observed by Nonaka et al. are also expected here[7-9]. While bistable operation had been anticipated in our earlier work[10], we now present clear-cut evidence of hysteresis over a range of bias conditions which leads to increased functionality of the routing switches, e.g. in time-slot interchange systems. The processing improvements which have led to the current generation of room-temperature CW devices have been the application of oxide confinement techniques to the epitaxial material to achieve low threshold current in the

VCSEL sections, and careful control of the chemically-assisted ion beam etching (CAIBE) process for etching the in-plane laser end mirrors.

Lately, much attention been focused on all-optical signal routing, wavelength switching and conversion by means of semiconductor optical amplifiers, due to their fast carrier and gain dynamics. This has been achieved using cross-gain compression[11], four-wave mixing, or Mach-Zehnder based cross-phase modulation[12]. Likewise, all-optical switching has also been achieved through electro-optic or third-order nonlinear effects in optical materials such as $LiNbO_3$ [13] or optical fiber itself. None of these approaches, though, offer the advantages of complete monolithic integration on a single chip, together with gain, in a design which is compatible with standard laser fabrication techniques. We demonstrate here a 1 x 3 routing switch which is capable of time division multiplexing and demultiplexing operations. The device is shown schematically in Figure 1, together with a SEM micrograph of a typical device. The main in-plane ridge-waveguide laser is 10 x 400 μm long, and its cavity contains three VCSEL output sections, each with an 8 μm^2 oxide aperture. The VCSEL sections have 10 x 200 μm side in-plane control lasers fabricated adjacent to them, and a passive in-plane laser mirror is etched on the opposite side of each VCSEL. The passive mirror section is required in order to oxidize the VCSEL mesa from all sides after defining the lasers by one-step two-level etching[14].

The fabrication process was as follows. After protecting the VCSEL apertures and depositing SiO_2 and Cr etch masks for the ridge waveguides and end the end mirrors respectively, the CAIBE etching was performed. In this way, the entire combined-laser structure was created in a single etching operation. The in-plane laser ridges were then protected from oxidation, and the samples were loaded into a furnace at 400 °C through which 3 slm N_2 gas (bubbled through 85 °C DI H_2O) flowed for 12 min. No delamination of the oxidized AlAs-based DBR structures was observed, as was noted previously by Choquette et al.[15]. Special care was taken, though, to not expose the samples to rapid temperature fluctuations (e.g., later rapid thermal alloying of the contacts) after oxidation. While the desirable effects of a single oxide aperture above and/or below the active region of a VCSEL for reducing its threshold current have been thoroughly documented[16], it was desired here to demonstrate the feasibility of monolithically integrating oxide-confined VCSELs and in-plane lasers to create optical routing switches using "standard" 850 nm epitaxial material with three 80 Å GaAs quantum wells.

Figure 2 shows the combined output of VCSELs 1 and 2 when both are biased above threshold and the on/off modulation signal shown is introduced to the main in-plane laser. The combined signal is detected by a large 1 cm^2 Si photodetector which is 3 cm from the wafer surface, and the contribution to the total power output from VCSEL 2 is shaded. A small-signal modulation of the main in-plane laser drive current may also be used, or the main laser may have cleaved facets for the purpose of introducing a modulation signal using an external fiber. The performance of the routing switches tested was not significantly different using the CAIBE-etched facets or one or more cleaved facets; thus the devices may be monolithically integrated with other components such as lasers and waveguides, or they may be used as stand-alone time-division multiplexers or demultiplexers with the outputs coupled into optical fibers. In Figure 2, the scattered light from the in-plane laser has been measured and subtracted from the combined signal to achieve the result shown. Note that when the either the main in-plane laser or one of the side in-plane control lasers is on, the associated VCSEL output is shut off. Here, the main in-plane laser modulation signal is inverted and transferred to the VCSEL outputs by means of the gain quenching phenomenon. When the main laser is lasing, the gain in the VCSEL sections is reduced, and the VCSEL threshold currents rise accordingly. When the VCSEL sections are biased just above threshold, their output is quenched to spontaneous emission levels (<10 μW) when the main laser is on. If the VCSEL drive current is too high, its output will be reduced somewhat (by ≈ 1 mW), but it does not shut off completely. The on/off contrast ratio is measured to be >20 dB, and the side in-plane control lasers have a negligible effect on the main in-plane laser output and vice versa.

In Figure 3, the hysteresis in the transfer characteristic between one VCSEL's output power and the output power of the main in-plane laser is shown. This was measured by ramping the drive current to the in-plane laser up and down while a fixed current was applied to the VCSEL during that time. If the VCSEL drive level was lowered, the loop size was smaller, as can be seen in the figure. At ≈ 1 mW VCSEL output or greater, the loop grew no bigger, and instead the whole loop moved upward as the VCSEL current increased since the VCSEL was not being fully quenched, as was mentioned above. The bistability of the coupled-laser routing switch is quite evident, and the loop has a trapezoidal shape because at intermediate in-plane power levels, it is possible for both lasers to lase simultaneously while the two modes are competing with each other for gain. The 8 μm^2 VCSEL threshold current increased from 2 mA with the main laser off to >5 mA when the in-plane laser output power was over 2.5 mW. The VCSEL threshold current did not increase indefinitely with increasing in-plane laser power, and this was attributed to filamentation in the in-plane laser cavity allowing the VCSEL to compete more effectively for gain in the shared cavity section. The hysteresis loop is traversed in the directions indicated. If one begins at the upper left corner with the VCSEL already lasing, the nominal (2 mA) VCSEL threshold current is in effect. As the in-plane laser begins to lase, the VCSEL gain decreases until the VCSEL is no longer lasing (upper traces). With the in-plane laser on, the VCSEL threshold current is increased, and the VCSEL remains off until the in-plane laser output falls below the point where the VCSEL can compete once again for some of the available gain (lower traces.) When the in-plane laser output returns to zero, the loop has been completed. This hysteresis may be used to buffer the output intensity of the VCSELs from random fluctuations in the input modulation signal level to the in-plane laser, and the bistability we have observed may be used for optical memory purposes as well. The control lasers could perform a reset function in an optical flip-flop formed by the main in-plane laser and the VCSEL, and the number of bits which could be stored is limited only by the number of intracavity VCSEL sections used. Furthermore, if the side in-plane control laser facets were anti-reflection coated for external signal input, the routing switch would be capable of multiplexing operations with wavelength conversion capability and gain to compensate for the coupling losses. This has been shown theoretically by Parker et al.[6] and demonstrated in principle by Tsuda et al. using a side-injection-light-controlled bistable laser diode[17]. Since the sensitivity of the control lasers would vary continuously with the input wavelength, the router could also perform a discrimination function for all-optical FM-to-AM signal conversion.

The low modulation frequency used here was intended primarily to demonstrate the functionality of the device, and the minimum rise time of the VCSEL outputs was limited by the driving apparatus (HP 8160A pulse generator) to ≈20 nsec. The epitaxial material used was intended primarily for VCSEL use and not for in-plane lasers, and the overall device geometry remains to be optimized for high-speed operation. The maximum switching frequency of the routing switches will ultimately be determined by the relaxation frequency of the in-plane lasers and the VCSELs used, unless the two-mode bistability arising from the shared gain region common to all the lasers is more fully utilized in a manner similar to Johnson et al.[4].

In other applications, the routing switch presented would be an effective output device for a time-slot interchange system, since the memory and routing functions are performed by the same device. Also, note that more than one of the VCSEL outputs can be on at the same time, which makes a simultaneous "broadcast mode" to all output channels possible. Such a feature is difficult to implement in some wavelength conversion schemes. If the natural variation in the output VCSEL wavelength were used or tuning were added to the output channels by means of mechanically changing the VCSEL cavity size, then several narrow-spaced output wavelengths could also be addressed by one or more input modulation signals.

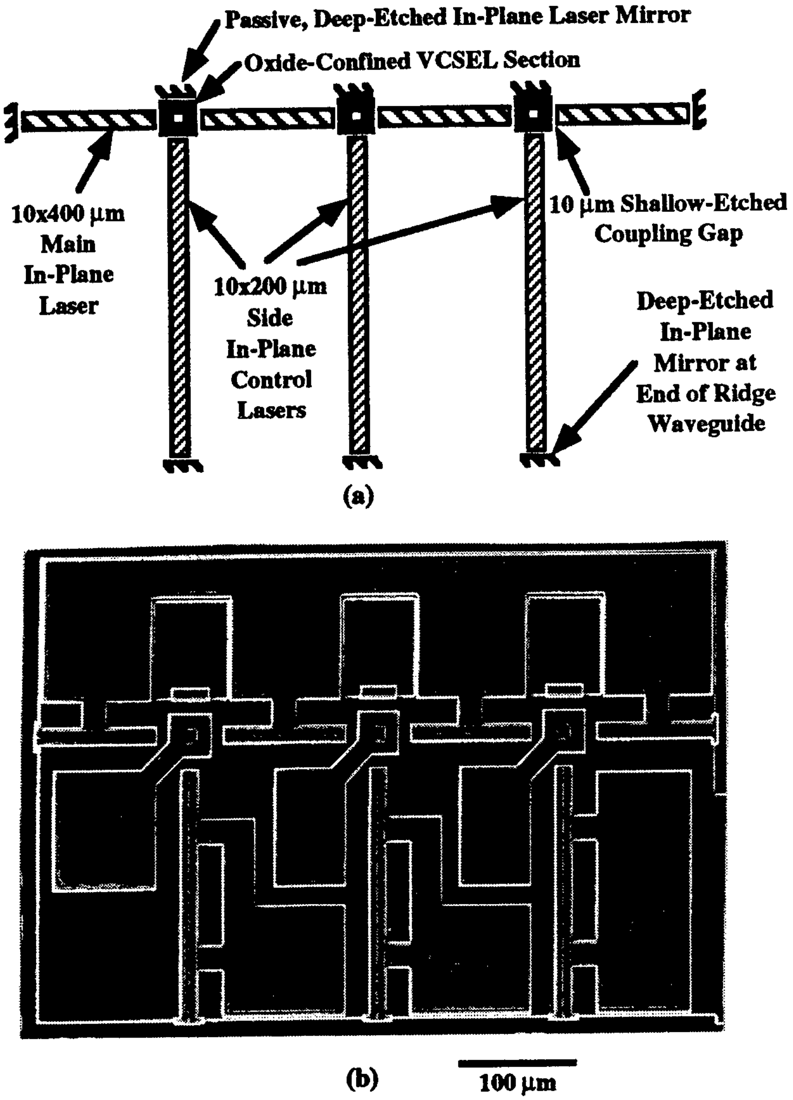

FIG. 1. (a) A schematic diagram of an all-optical 1×3 routing switch, and (b) a SEM micrograph of a completed device.

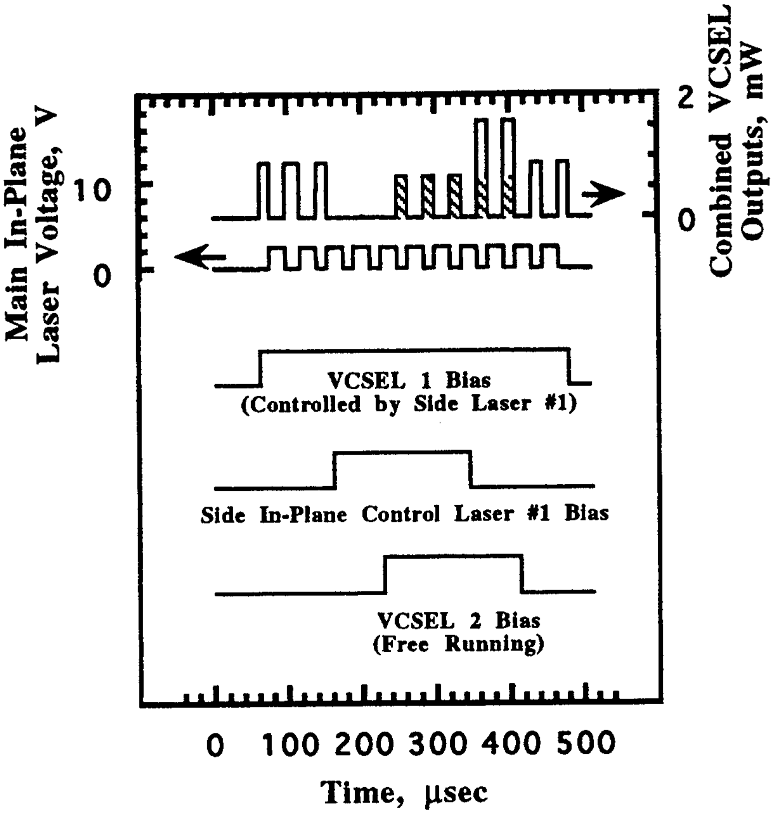

FIG. 2. Demonstration of the routing switch operation. Side control laser 1 is used to switch off VCSEL 1's output, while VCSEL 2 is free running. Both outputs may be on simultaneously.

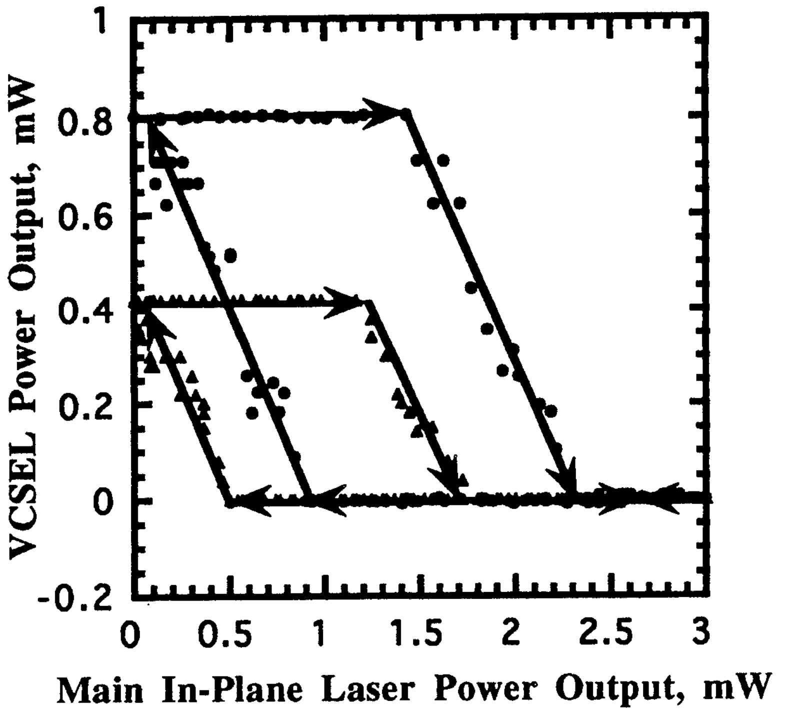

FIG. 3. Hysteresis in the routing switch input/output transfer characteristic. (●) Initial VCSEL output ≈0.8 mW, and (▲) initial VCSEL output ≈0.4 mW.

Conclusions and Future Work

In conclusion, we have demonstrated bistable operation in intracavity-coupled in-plane lasers and oxide-confined VCSELs. These were implemented in a monolithically-integrated all-optical 1 x 3 routing switch which operated CW at room temperature. The on/off contrast ratio was >20 dB, and there was negligible crosstalk between the output devices. The routing switches have a thresholding feature due to the hysteresis in the output power vs. input power transfer characteristic, and they have time division multiplexing and demultiplexing capabilities as well. The goals of the original Expert in Science and Engineering grant and its extension have been largely met; that is, the oxidation furnace for AlGaAs materials was constructed, VCSELs and in-plane lasers were made in part by using this system, and the resulting routing switches that were fabricated made room-temperature characterization of these devices possible. A clear-cut demonstration was made of the two-mode bistability which had long been predicted in intracavity-coupled lasers with overlapping gain regions, and the opening of the hysteresis loop in input power-output power space has been measured. The foundation has thus been laid for future work in which subsystems employing the all-optical switching devices developed here are demonstrated, including time-slot interchange circuits and transmitters for dense wavelength-division multiplexed transmission systems.

References

[1] D. B. Shire, M. A. Parker, P. D. Swanson, J. S. Kimmet, and C. L. Tang, Appl. Phys. Lett. **66**, 1717 (1995).

[2] D. B. Shire, M. A. Parker, and C. L. Tang, IEEE Photon. Technol. Lett. **8**, 188 (1996).

[3] C. L. Tang, A. Schremer, and T. Fujita, Appl. Phys. Lett. **51** 1392 (1987).

[4] J. E. Johnson, C. L. Tang, and W. J. Grande, Appl. Phys. Lett. **63** 3273 (1993).

[5] M. A. Parker and D. B. Shire, Appl. Phys. Lett. **70** 146 (1997).

[6] M. A. Parker and D. B. Shire, J. Appl. Phys., submitted for publication (1997).

[7] K. Nonaka and T. Kurokawa, Electron. Lett. **31** 1865 (1995).

[8] K. Nonaka, Y. Noguchi, H. Tsuda, and T. Kurokawa, in *Proc. 14th IEEE International Semiconductor Laser Conference* 229 (1994).

[9] K. Nonaka and T. Kurokawa, in *Proc. International Topical Meeting on Optical Computing - OC '96* 48 (1996).

[10] D. B. Shire, C. L. Tang, M. Hong, and J. D. Wynn, IEEE Photon. Technol. Lett. **8**, 1537 (1996).

[11] J. M. Wiesenfeld, J. S. Perino, A. S. Gnauck, and B. Glance, Electron. Lett. **30**, 720 (1994).

[12] B. Mikkelson, T. Durhuus, C. Joergenson, R. J. S. Pedersen, C. Braagaard, and K. E. Stubkjaer, Electron. Lett. **30**, 260 (1994).

[13] R. C. Alferness, N. P. Economou, and L. L. Buhl, Appl. Phys. Lett. **38**, 214 (1981).

[14] W. J. Grande, J. E. Johnson, and C. L. Tang, Appl. Phys. Lett. **57** 2537 (1990).

[15] K. D. Choquette, K. M. Geib, H. C. Chui, B. E. Hammons, H. Q. Hou, T. J. Drummond, and R. Hull, Appl. Phys. Lett. **69** 1385 (1996).

[16] K. D. Choquette, W. W. Chow, M. Hagerott Crawford, K. M. Geib, and R. P. Schneider, Jr., Appl. Phys. Lett. **68** 3689 (1996).

[17] H. Tsuda, K. Nonaka, K. Hirabayashi, H. Uenohara, H. Iwamura, and T. Kurokawa, Appl. Phys. Lett. **63** 3116 (1993).