CThM26 Fig. 2. Experimental setup.

CThM26 Fig. 3. The normalized transmission variation of (a) the 'initially off' and (b) the 'initially on' devices.

coupling length, two kinds of device (the 'initially off' and the 'initially on') are made, which may be switched respectively 'on' or 'off' by photo-induced carrier density variation in the upper waveguide.

The light source used is a gain-switched DFB laser with a pulsedwidth of 5 ps and a repetition rate of 250 MHz at $\lambda = 1548$ nm. An EDFA amplifies the optical signal to 15 dBm, which may be reduced by a variable optical attenuator (VOA). A fiber polarization controller following the variable attenuator ensures TE polarization launch. The fiber coupling loss is about 3 dB. The output signal level is filtered at the DFB laser wavelength and measured by an optical power meter.

Both kinds of devices have been tested. Figure 3 shows the optical self-switching characteristics of the switches. It is clear that with the 'initially off' device, a switching contrast of about 12 dB is achieved while the contrast is as high as 23 dB for the 'initially on' device. The 'initially off' device shows a gradual increase in transmission while the usually on device shows much sharper switching characteristics, with a switching of 20 dB happening in the input power range of 10 and 14 dBm. The latter result confirms that the switching is due to change in refractive index caused by the photo-carrier rather than simply gain or absorption saturation, because the variation slope would be 1 on the log-log plot for simple saturation.

A novel compact integrated nonlinear optical switch has been demonstrated. Using a high-power picosecond pulse of 5-ps pulse-width and 250-MHz repetition rate, all-optical switching with a contrast ratio of 23 dB has been achieved using an in-fiber input power lower than 14 dBm (100 pJ/pulse). The switch speed depends on the carrier sweep-out time, which can be reduced to the 10 ps range by either applying a reverse bias or by introduction of carrier recombination centres in the active layer.

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CThM27

High-speed transparent indium-tin-oxide based resonant cavity Schottky photodiode with $\text{Si}_3\text{N}_4/\text{SiO}_2$ top Bragg mirror

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Photodetectors demonstrating high bandwidth-efficiency (BWE) products are required for high-performance optical communication and measurement systems.¹ For conventional photodiodes the BWE product is limited due to the bandwidth-efficiency trade-off. Resonant cavity enhanced (RCE) photodetection scheme offers the possibility to overcome this limitation.² Very high BWE products are achieved using Schottky and p-i-n type RCE photodiodes, which could not be reached with conventional detector structures.^{3,4} Even better performances should be possible for RCE Schottky photodiodes if one can get rid of the optical losses and scattering caused by the Schottky metal, Au, which also serves as the top mirror of the resonant cavity. The transparent, low resistivity material indium-tin-oxide (ITO) is a potential alternative to thin semi-transparent Au as a Schottky-barrier contact material.^{5,6} In this paper, we report our work on high-performance ITO-based RCE Schottky photodiodes.

We deposited ITO by RF magnetron sputtering in an Ar environment from a composite target containing by weight 90% In_2O_3 and 10% SnO_2 . Thin-film characteristics of ITO are analyzed before device fabrication. Resistivity of our ITO film is calculated as $2 \times 10^{-4} \Omega\text{-cm}$ from 4-probe measurements. This value decreases to 1.5×10^{-4} and $1.2 \times 10^{-4} \Omega\text{-cm}$ under anneal temperatures of 300°C and 400°C, respectively. Transmission experiments showed that the transmittivity of a 150-nm-thick ITO film is around 87% at 840 nm, which is almost independent of the film-deposition rate and annealing temperature. Reflectivity at the same wavelength is around 12%, which indicates that the absorption in ITO is less than a few percent. Ellipsometry measurements indicate that the as-grown ITO film has a refractive index of 1.99. This value

$\text{Si}_3\text{N}_4/\text{SiO}_2$ Top DBR		
ITO-Schottky layer		
120 nm	GaAs (Active Layer)	N^-
30 nm	Graded Interface	N^-
160 nm	$\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$	N^-
400 nm	$\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$	N^+
230 nm	$\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$	Undoped
$\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}/\text{AlAs}$ Bottom DBR (19 Pairs)		
Semi-Insulating GaAs Substrate		

CThM27 Fig. 1. Schematic representation of the layer structure of the RCE Schottky photodiode.

decreases to 1.85 for annealing temperature of 450°C.

Figure 1 shows the layer structure of the RCE Schottky photodiode. The resonant cavity is formed by a MBE-grown $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}/\text{AlAs}$ distributed Bragg reflector (DBR) bottom mirror and a PECVD-grown $\text{Si}_3\text{N}_4/\text{SiO}_2$ DBR top mirror, both centered at 840 nm. The samples are fabricated by a microwave-compatible fabrication process. Fabrication started with the formation of ohmic contacts to n^+ layers. Mesa isolation was followed by a Ti-Au interconnect metallization. Then, a 100-nm-thick ITO film as the Schottky layer and a Si_3N_4 passivation layer was deposited. Finally, a thick Ti-Au layer was evaporated to form an air-bridge connection between the interconnect and the ITO Schottky layer.

Photoresponse measurement setup consisted of a tungsten-halogen projection lamp, a monochromator, a multimode fiber, a light-wave probe and a probe station. Figures 2(a) and 2(b) show the measured spectral quantum

CThM27 Fig. 2. Experimental spectral photoresponse (a) without top DBR, (b) with top DBR.

CThM27 Fig. 3. Pulse response of a $8 \times 14 \mu\text{m}^2$ ITO-RCE Schottky photodiode.

efficiencies of devices without and with top Bragg mirror, respectively. The peak quantum efficiency before top DBR deposition was 33% and increased to a maximum of 59% for 5 pair top DBR.

High-speed measurements were made with 1-ps optical pulses obtained from a Ti:Sapphire laser operating at 840 nm. Figure 3 shows the measured photodiode output with 15-ps FWHM, which reduces to 12 ps after deconvolving the 50-GHz scope response, corresponding to a 3-dB bandwidth of 37 GHz and a BWE product of more than 20 GHz.

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CThM28

High-power and picosecond pulse generation from a passively Q-switched tapered InGaAs/GaAs laser

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High-power picosecond optical pulses are required for a wide range of applications includ-

CThM28 Fig. 1. Schematic diagram of the experimental setup and the laser.

ing optical switching, instrumentation, ranging, pumping, sensing, and spectroscopy.^{1,2} Q-switched pulses having an energy of 300 pJ and a duration of 40 ps were obtained from a 100- μm wide AlGaAs diode laser.³ However, widening the waveguide width generally results in a loss of spatial coherence. A majority of applications require both spatial and spectral coherence in the output optical pulse.

Tapered waveguides have been used for enhancing pulse powers in Q-switched AlGaAs and InGaAsP (1.5 μm) lasers.^{4,5} Here we report, for the first time to our knowledge, passively Q-switched pulses with 1.53 W peak power and 41-ps FWHM from an InGaAs/GaAs (970 nm) double-contact tapered semiconductor laser in a well defined single lobed far-field.

Figure 1 shows a schematic diagram of the proposed laser diode and the experimental setup. The laser consists of a non-tapered waveguide (absorber), which is 2- μm wide and 100- μm long and a tapered gain section (500 μm).

We have fabricated the proposed two-section ridge-waveguide tapered device from an InGaAs/GaAs GRINSCIT 2 QW wafer grown by MBE. The laser, tested as cleaved, has a threshold current of 90 mA with a front facet slope efficiency of 0.32 W/A under cw driving conditions. The intercontact resistance of the device is 600 Ω , and the tapered section of the device is 50 Ω matched.

The gain section is pumped with 800-ps FWHM electrical pulses of 1.2 A and 1 A at a repetition rate of 10 kHz. A reverse dc-bias (V_b) in the range of 0V to -9V is applied to the absorber section to enhance the absorption. The pulses generated are measured with a 25-GHz photodiode, and the results are tabulated in Table I.

A symmetric Q-switched pulse [Fig. 2(a)] of up to 1.53 W peak power (63 pJ) and 41-ps pulsewidth are obtained under 1.2 A driving conditions. A tail appearing at low reverse bias voltages is eliminated at $V_b = -9\text{V}$.

The far-field pattern for quasi-cw and Q-switched operation is shown in Fig. 2(b). The far-field has a width of 2.6° FWHM and 14° at $1/e^2$ under quasi-cw operation. However

(a)

(b)

CThM28 Fig. 2. Q-switched pulse at $V_b = -9\text{V}$ under 1.2A (a) and far-field distribution of the quasi-cw and Q-switched pulses (b).

under Q-switched operation, a high-quality single-lobed distribution is observed with a far-field of 4° FWHM and a $1/e^2$ width of 7°. This appears as under short pulse driving conditions insufficient time exists to cause mode switching.

It is finally observed that the $1/e^2$ width of the near-field distribution decreases from 19.3 μm under quasi-cw operation to 17.3 μm under Q-switched operation, indicating that the mode nearly fills the waveguide.

Q-switched pulses of up to 1.53 W peak power (63 pJ), 41-ps duration and separately down to 29 ps are generated in a single spatial mode from an InGaAs/GaAs double-contact tapered ridge-waveguide laser at 970 nm.

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CThM28 Table I. Pulsewidth, Peak Power and Energy of the Q-Switched Pulses

Driving Current (A)	V_b (V)	Pulsewidth (ps)	Peak power (W)	Pulse energy (pJ) at fwhm
1.2	0	45	1.23	55
	-3	46	1.25	57.5
	-9	41	1.53	63
1	0	29	0.86	25
	-3	34	0.83	28
	-7.5	29	0.912	27