

sistently produce lower compression currents than time-domain measurements for all tested photodetectors. The difference can be explained by the delayed evolution of the space-charge field and by the fact that saturation is frequency dependent. High-frequency signals become saturated at much lower levels than low-frequency signals. Frequency-domain measurements are usually performed at high frequencies, whereas time-domain measurements represent the average saturation level over a broad frequency range. We report details of measurements, including the bias dependence, simulation results, buildup time of the space-charge field, and comparison between the time- and frequency-domain measurements.

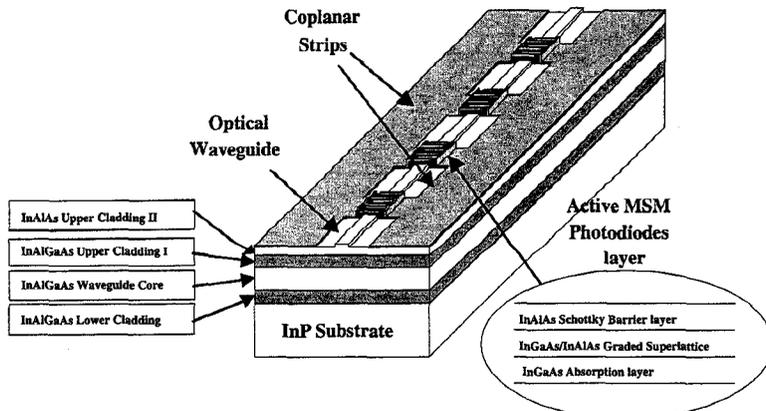
1. K.J. Williams, R.D. Esman, M. Dagenais, J. Lightwave Technol. **14**, 84 (1996).
2. K.J. Williams, R.D. Esman, S. Williamson, J. Valdmanis, K. Al-Hemyari, J.V. Rudd, IEEE Photonics Technol. Lett. **9**, 812 (1997).
3. L.Y. Lin, M.C. Wu, T. Itoh, T.A. Vang, R.G. Muller, D.L. Silva, A.Y. Cho, IEEE Photonics Technol. Lett. **8**, 1376 (1996).

CThM3 11:00 am

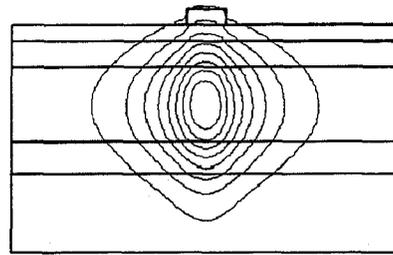
Long-wavelength velocity-matched distributed photodetectors

T. Chau, L. Fan, D.T.K. Tong, S. Mathai, M.C. Wu, D.L. Sivco,* A.Y. Cho,* UCLA, Electrical Engineering Department, 66-147D Engineering IV, Box 951594, Los Angeles, California 90095-1594; E-mail: wu@ee.ucla.edu

High-power, high-speed photodetectors are a key component in microwave fiber-optic links, optoelectronic generation of microwaves, and millimeter waves.¹ Previously, we have reported a GaAs/AlGaAs velocity-matched distributed photodetector (VMDP) that operates at 860 nm and demonstrated its potential for high-saturation photocurrents.² For applications in rf photonic systems, however, InP-based long-wavelength photodetectors operating at 1.3 or 1.55 μm are required. In this paper, we report on the experimental results of InGaAs/InAlGaAs/InP VMDP.



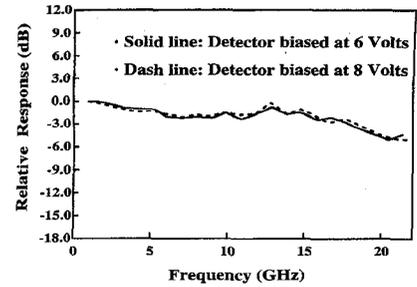
CThM3 Fig. 1. Schematic structure of long-wavelength velocity-matched distributed photodetector (VMDP).



CThM3 Fig. 2. Contour plot of the fundamental mode field amplitude in the passive optical waveguide using BPM simulation. See Fig. 1 for layer structure.

The schematic structure of the VMDP is illustrated in Fig. 1. Active metal-semiconductor-metal (MSM) photodiodes are periodically distributed on top of a passive optical waveguide. Optical signal is evanescently coupled from the passive waveguide to the active MSM photodiodes. Photocurrents generated from each MSM photodiode are added in phase through a 50- Ω coplanar strip (CPS) microwave transmission line that is velocity matched to the optical waveguide. The MSM photodiodes serve two functions here: they generate photocurrents and provide the periodic capacitance loading needed for velocity matching. The VMDP design allows the passive waveguide, the active photodiodes, and the microwave coplanar strips to be independently optimized. In Fig. 1, the active MSM photodiode consists of an InGaAs absorption layer, an InGaAs/InAlAs graded superlattice layers, and an InAlAs Schottky-barrier enhancement layer. At 10-V bias, a dark current of 190 pA is measured for an $11 \times 48\text{-}\mu\text{m}^2$ MSM photodiode. For a 1.2-mm-long VMDP with 12 $11 \times 48\text{-}\mu\text{m}^2$ MSM photodiodes, a dark current of 25 nA is measured at 10-V bias.

Figure 2 shows the contour plot of the fundamental mode field amplitude in the passive waveguide using beam propagation method (BPM) simulation. The VMDP is designed so that only the fundamental mode exists in the optical waveguide and the active photodiode regions. Simulation results with the BPM method indicate a 4% scattering loss and 7% absorption loss per photodiode. Scattering loss can be reduced to 1% per diode by optimizing the geometric structure of the active photo-



CThM3 Fig. 3. Measured frequency response of long-wavelength VMDP (12 photodiodes, 1.2 mm long).

diode. The device under test is 1.2 mm long and consists of 12 MSM photodiodes. In this experiment, optical lithography is employed to pattern the MSM photodiodes. Both the fingers and the spacing are 1 μm wide. After antireflection (AR) coating, a quantum efficiency of 34% was measured (this includes the coupling loss from optical fiber). High-saturation current measurement with a high-power erbium-doped fiber amplifier is in progress.

The frequency response of the VMDP is characterized by the optical heterodyne method.^{4,5} The system consists of two external cavity tunable lasers at 1.55 μm ; the frequency of each laser can be tuned in 1-GHz steps. The optical signals are combined by a 3-dB coupler and coupled to the VMDP through a fiber pickup head. The microwave signal generated by optical mixing in the VMDP is collected at the output end of the CPS by a 50-GHz picoprobe (GGB Industries), which is connected to an rf-power sensor and monitored by an rf-power meter. The calibrated frequency response of long-wavelength VMDP is shown in Fig. 3. A 3-dB bandwidth frequency of 18 GHz is measured. By scaling down the MSM to 0.1 μm scale, a frequency response >100 GHz is expected.

In summary, we have experimentally demonstrated a high-speed, high-power long-wavelength VMDP using optical lithography. A 3-dB bandwidth of 18-GHz and an overall quantum efficiency of 34% have been achieved.

This project is supported by TRW, ONR MURI on RF Photonics, ARO, JSEP, and UC MICRO.

*Lucent Technologies, Bell Laboratories, Murray Hill, New Jersey 07974

1. C.H. Cox III, IEEE Proc. J. **139**, 238-242 (1992).
2. L.Y. Lin, M.C. Wu, T. Itoh, T.A. Vang, R.E. Muller, D.L. Sivco, A.Y. Cho, IEEE Trans. Microwave Theory Tech. **45**, 1320-1331 (1997).
3. H. Kogelnik, "Theory of optical waveguides," in *Guided-Wave Opto-Electronics*, T. Tamir, ed. (Springer-Verlag, Berlin, 1988).
4. T. Hawkins II, M.D. Jones, S.H. Pepper, J.H. Goll, J. Lightwave Technol. **9**, 1289-1294 (1991).
5. P.D. Hale, D.A. Humphreys, A.D. Gifford, SPIE **2149**, 345-356, 1994.

Thursday, May 7