III-V DEVICE TECHNOLOGIES FOR LIGHTWAVE APPLICATIONS

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High-performance, reliable III-V devices are a basic part of AT&T's lightwave transmission systems. This paper describes advances in lasers, photodetectors, optical amplifiers, superlattice devices, monolithically integrated structures, and switching devices and their role in AT&T lightwave systems.

Introduction

The research, development, and manufacturing of III-V devices in AT&T provides new avenues for AT&T lightwave transmission systems, switching systems, and high-speed electronic processing systems. Advances in these system technologies have helped AT&T become a major player in providing products and services in the information age. The first field trial of an AT&T lightwave transmission system took place in Chicago in 1977. Since then, AT&T has installed numerous lightwave transmission systems across the U.S. and recently completed the installation of the first transatlantic lightwave transmission system (TAT-8).

The two major technological advances responsible for the lightwave revolution in telecommunications are: (a) the development of low-loss silica (glass) fibers that act as the transmission medium and (b) the development of reliable III-V photonic devices. The enormous fiber bandwidth—along with the high-speed capabilities of lightwave sources, detectors, and information-processing electronics—gives the lightwave transmission system a vast information-carrying capacity at a relatively low cost.

Figure 1 shows the rapid improvement in cost effectiveness, expressed as cost per bit per kilometer, together with the key components in associated III-V technologies. A one-hundred-fold decrease in cost per unit capacity occurred in one five-year period. The AT&T FT Series G system is currently being installed at equivalent data rates of 3.4 gigabits per second (Gb/s) (i.e., two channels, each operating at 1.7 Gb/s). Laboratory transmission experiments have been carried out at data rates of 16 Gb/s using time-division-multiplexing technology.

This paper describes the applications of III-V devices to lightwave technology and builds upon our earlier article,[1] emphasizing new concepts in device design and new trends in device technologies.

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Principal Lightwave System Configurations

Lightwave system configurations can, in general, be divided into two categories: *direct-detection* and *coherent-detection* systems. (See Figure 2.) In a digital direct-detection system, the light from the source is digitally encoded by directly applying the encoded current to the source. The intensity-modulated light signal travels through the fiber and to a receiver where a photodetector converts the optical signal into an electrical signal from which the original coded information is retrieved using a series of functions such as amplification, filtering, and timing. Almost all AT&T lightwave systems in the field use the digitally encoded direct-detection format.

In coherent transmissions, the encoding takes the form of amplitude, frequency, or phase variation in the optical beam. The received signal is mixed with the light from a local oscillator laser at the receiver-photodiode, generating a beat signal that falls in the microwave range. The transmitter and the local oscillator laser must emit at signal wavelengths with narrow spectral width [< 10 megahertz (MHz)] and must exhibit wavelength tunability. Coherent-detection techniques offer the potential for (a) much higher receiver sensitivity than direct detection and (b) channel selection in a densely packed wavelength-division-multiplexing (WDM) system. (See Panel 1 for a list of terms and acronyms used in this paper.)

Sources

In lightwave transmission systems, light-emitting diodes (LEDs) or lasers are used as sources of light. These devices are fabricated from multilayered structures of compound semiconductors epitaxially grown on a single-crystal substrate. The epitaxial growth process preserves the crystalline symmetry throughout the entire multilayered structure. (See the article by Johnston et al. in this issue of the *AT&T Technical Journal.*[2])

LEDs. LEDs are used as a source for *optical data link* applications in which the data rates are less than

Panel 1. Acronyms in This Paper

AlGaAs	aluminum gallium arsenide
APD	avalanche photodiode
Au	gold
CMBH	capped-mesa buried heterostructure laser
Cr	chromium
CSBH	channeled-substrate buried heterostructure laser
DFB	distributed-feedback laser
FET	field-effect transistor
FIT	one failure in 10^9 hours
FSK	frequency-shift-keying
InGaAsP	indium gallium arsenide phosphide
JFET	junction field-effect transistor
LED	light-emitting diodes
MISFET	metal-insulator-semiconductor field-effect transistor
MOCVD	metal-organic chemical vapor deposition
MQW	multiquantum well
PIN	positive-intrinsic-negative
S-SEED	symmetric self-electro-optic-effect device
SAM	separate absorption and multiplication
SEED	self-electro-optic-effect device
WDM	wavelength-division multiplexing
Zn	zinc

about 500 megabits per second (Mb/s) and the transmission distances do not exceed a few kilometers. LEDs emitting near 0.85 μm and fabricated using the aluminum gallium arsenide (AlGaAs) material system are used for the AT&T ODL® 40 and ODL 50 product families. These devices are used in the AT&T 5ESS® switching systems.

LEDs are also used as sources for systems operating near 1.3 μm, where fiber loss is considerably smaller than at 0.85 μm, and where the chromatic dispersion is near zero. These devices are fabricated using the indium gallium arsenide phosphide (InGaAsP) material system. The schematic cross section of a surface-emitting LED used in the ODL 200 product family is shown in Figure 3. The light is emitted from the top surface when current is injected into the device. The curved, hemispherical surface of the top layer near the light-emitting region acts as a collimating lens and allows a larger fraction of the emitted light to be coupled into a fiber. The
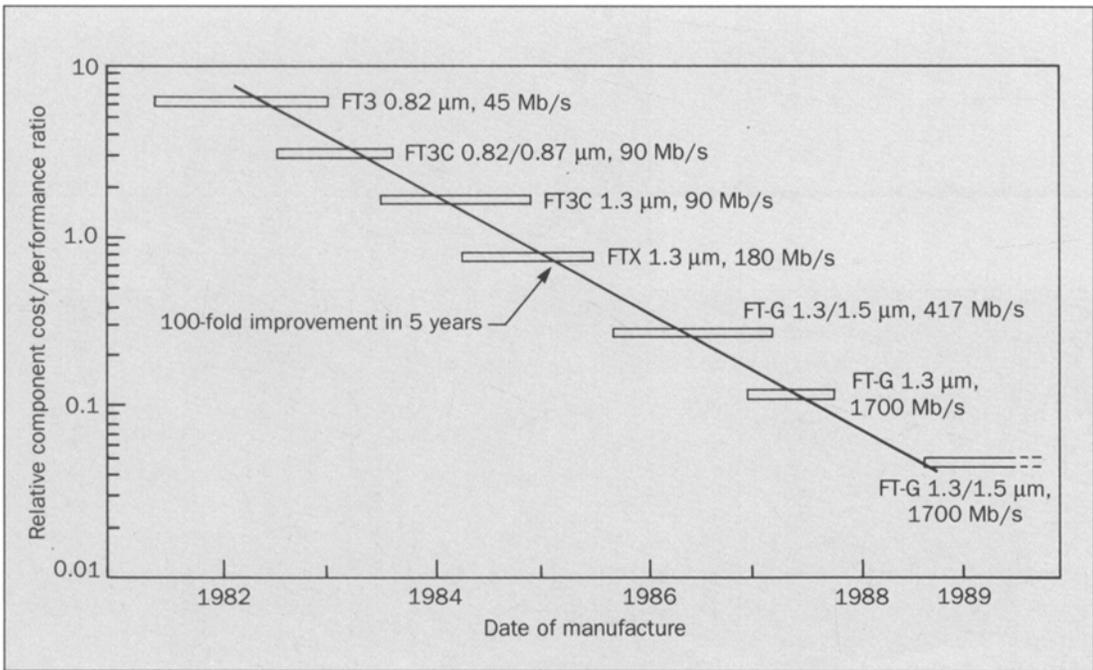
Figure 1. Performance and cost of AT&T lightwave transmission systems. Key III-V photonic devices are also shown.
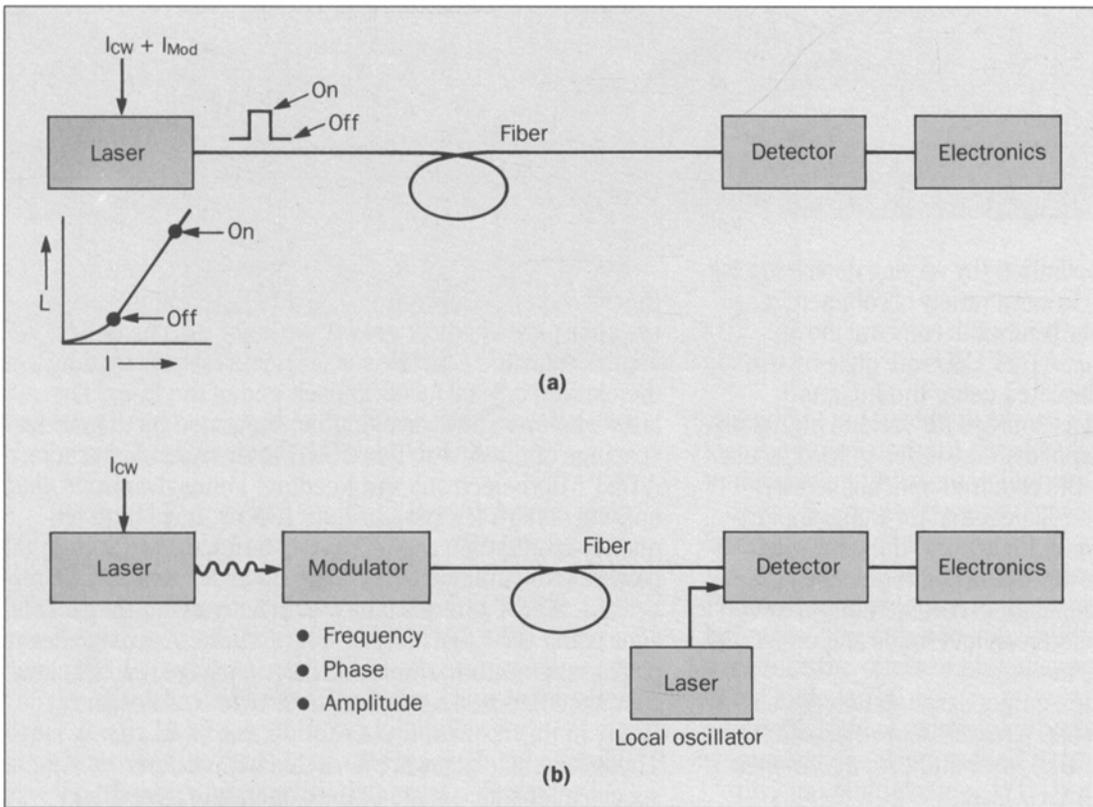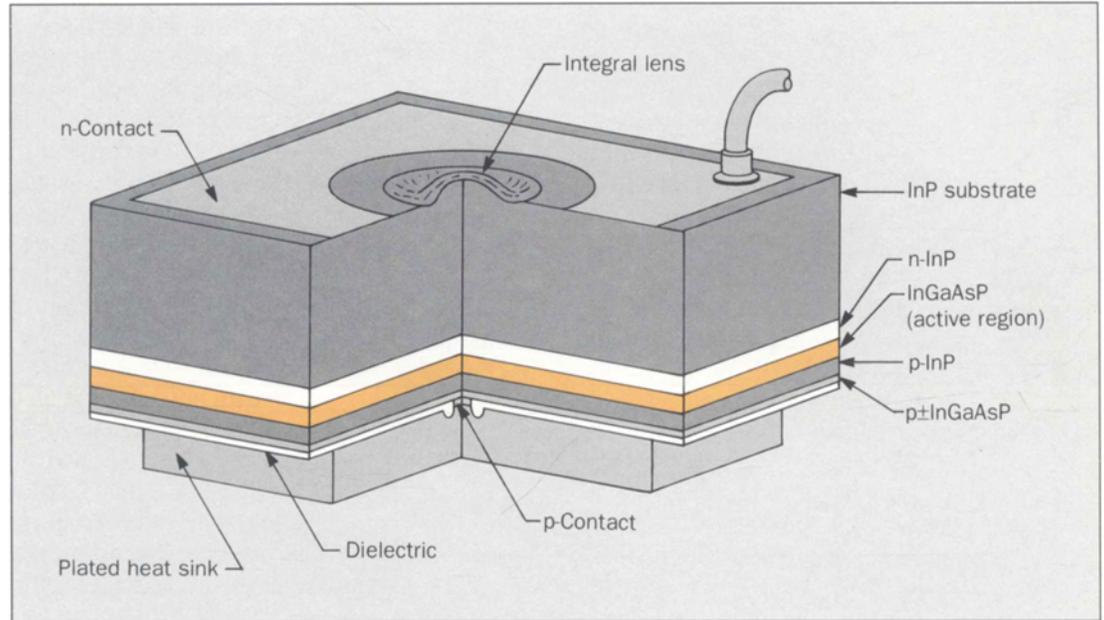

Figure 2. Simplified block diagrams of (a) direct-detection and (b) coherent-detection lightwave systems. Lasers or LEDs are used as sources for direct detection.

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Figure 3. Schematic of a surface-emitting LED. The InGaAsP (λ ~ 1.3 μm) layer surrounded by p-InP and n-InP layers is the light-emitting region. The lens helps in reducing the beam divergence.

basic LED design can be optimized (by varying doping levels, active-layer thickness, etc.) to suit a variety of commercial applications. In general, higher bandwidth comes at the expense of lower output power. AT&T LEDs are quite robust.

Lasers. Lasers fabricated using the InGaAsP material system are used as sources for various high data-rate, long-haul trunking applications. Index-guided lasers fabricated at AT&T have the required optical linearity, temporal stability, and long life needed for these applications. The index-guiding is achieved by "burying" the light-emitting region in lower index and higher bandgap layers, which allows both electrical confinement of the radiatively recombining electrons and holes and optical confinement of the lasing mode.

Two types of index-guided laser structures currently manufactured at AT&T are: the *channeled-substrate buried heterostructure* (CSBH) laser and the *capped-mesa buried heterostructure* (CMBH) laser.

Cross sections of these devices are shown in Figures 4 and 5. They are fabricated using liquid-phase- or vapor-phase-epitaxy growth techniques. The optical feedback for the CSBH laser (Figure 4) is provided by the cleaved crystal facets at each end of the laser. The laser emits at a few wavelengths, separated by the mode spacings of the cavity. The CSBH lasers manufactured at AT&T Microelectronics in Reading, Pennsylvania operate at high temperatures (> 120°C), have high frequency-modulation capability (> 9 GHz), and emit high powers [> 50 milliwatts (mW)].

AT&T offers a family of laser transmitter packages using the CSBH lasers. They are the Astrotec® laser package, the submarine cable laser package, and the low-cost uncooled package. (See the article by Alles and Brady in this issue of the *AT&T Technical Journal*.[3]) These laser packages are available with different specifications for optical output, operating speed, and
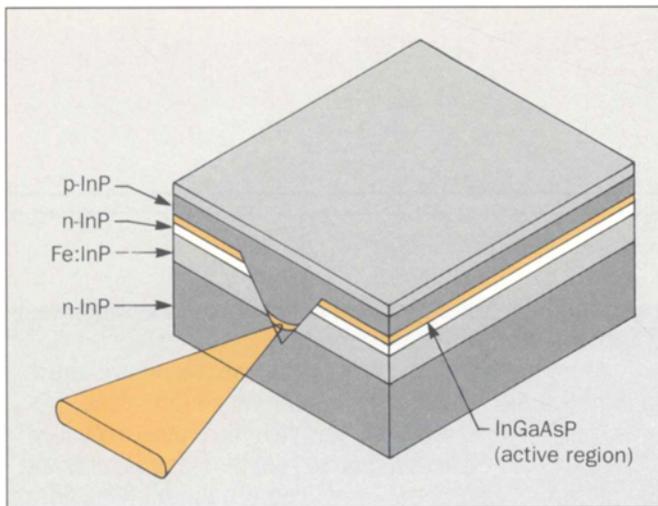
Figure 4. Schematic of a channeled-substrate buried heterostructure (CSBH). The light-emitting region is the small InGaAsP layer (~ 1.5 μm × 0.15 μm) in the V-groove. This laser source is used in the AT&T FT Series G transmission system.
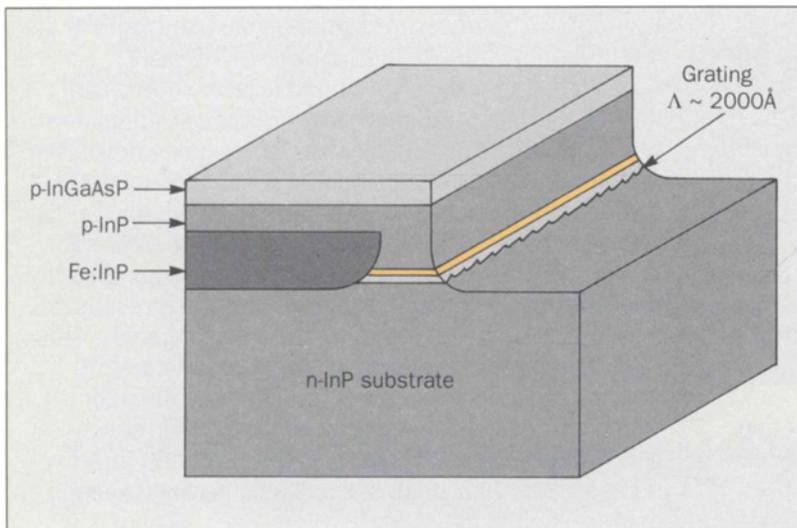

Figure 5. Schematic of capped-mesa buried heterostructure (CMBH) distributed-feedback laser. The diffraction grating near the active region provides frequency-selective feedback and makes the laser emit in a single frequency.

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wavelength, and are used in the FT Series G system and in submarine cable, loop feeder, and distribution applications.

Suitably designed multiwavelength lasers, emitting near 1.3 μm, can be used as sources for products with a bit-rate distance of less than 80 Gb/km. For higher data rates or for larger regenerator spacing, single wavelength sources are preferred to reduce the chromatic dispersion penalty. For systems operating near 1.55 μm with conventional silica fibers, high chromatic dispersion [~ 15 picoseconds per kilometer per nanometer (ps/km-nm)] limits the applicability of multi-wavelength lasers to very low data rates. Dispersion-

shifted fibers (i.e., fibers whose zero dispersion point and loss minimum occur at about 1.55 μm) allow the use of multiwavelength lasers in high data-rate systems.

Single-wavelength distributed-feedback (DFB) lasers, developed at AT&T Bell Laboratories and manufactured by AT&T Microelectronics in Reading, Pennsylvania, are used for many digitally encoded lightwave-transmission applications where it is necessary to reduce the effect of fiber dispersion. Applications could include:

- An upgrade of existing FT Series G routes in which more channels are added by using wavelength-division-multiplexing (WDM) technology
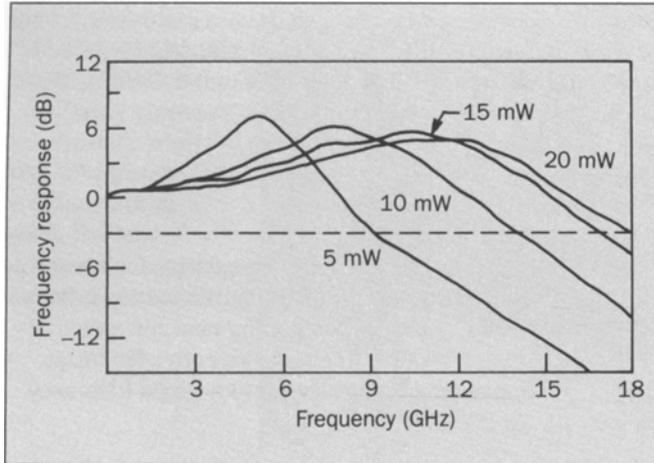
Figure 6. Small signal modulation response of a DFB laser under different bias conditions. Laser bandwidth increases with increasing output power reaching a value of 17 GHz at 20 mW.

- The next generation of submarine cable systems that operate at higher data rates with larger repeater spacings

- Commercial applications in which the repeater spacings are too large and/or the zero dispersion wavelength of the fiber is not precisely controlled.

The DFB laser has a diffraction grating incorporated into the structure (by etching, for example) prior to the epitaxial growth of the various layers. (See Figure 5.) The grating provides optical feedback at a fixed wavelength determined by the periodicity of the grating. CMBH DFB lasers have been fabricated that operate at high temperatures (> 100°C), have high modulation bandwidths (> 7 GHz), emit high powers (> 30 mW) in a single frequency, and have operating lifetimes comparable to those of multifrequency CSBH lasers.

AT&T offers a wide range of DFB laser transmitter packages for operation near 1.3 μm and 1.55 μm in the Astrotec laser system module and the submarine

cable module. Fiber-pigtailed optical isolators can be easily incorporated with either module.

A modification of the DFB laser structure shown in Figure 5 has been developed for very high-speed operation (> 10 GHz). This new structure uses very low-capacitance, semi-insulating current-blocking layers, and metallization schemes to enhance both the high-speed modulation response and output power of the laser. Figure 6 shows the measured small-signal bandwidth at different output powers of a high-speed DFB laser.

Single-wavelength, tunable laser sources are needed for coherent optical transmission systems. Currently, two types of tunable sources are being developed for coherent transmission applications. The emission wavelength of the two-section DFB laser (Figure 7a) can be varied by injecting a small modulation current into one of the two sections. The current modulates the refractive index of the light-emitting region, which results in modulation of the emission wavelength. Sources of this type have been used in a laboratory frequency-shift-keying (FSK) coherent transmission experiment in which a 6-decibel (dB) improvement in receiver sensitivity over direct detection was observed. An improvement greater than 10 dB is expected after optimization of the receiver configuration.

The emission wavelength of the device shown in Figure 7b can be varied over a much wider range [~ 60 angstrom (Å)] and can be used as the local oscillator laser for an optical coherent-transmission system. The device operates in a distributed Bragg reflector configuration in which the frequency selectivity is provided by a diffraction grating etched into a waveguide monolithically coupled to the light-emitting region. The current through the phase tuning and the frequency tuning sections helps change the index of the waveguide, which results in a continuous change in the emission wavelength.

Photodetectors

In lightwave systems, the photodetectors perform the important function of transforming the optical
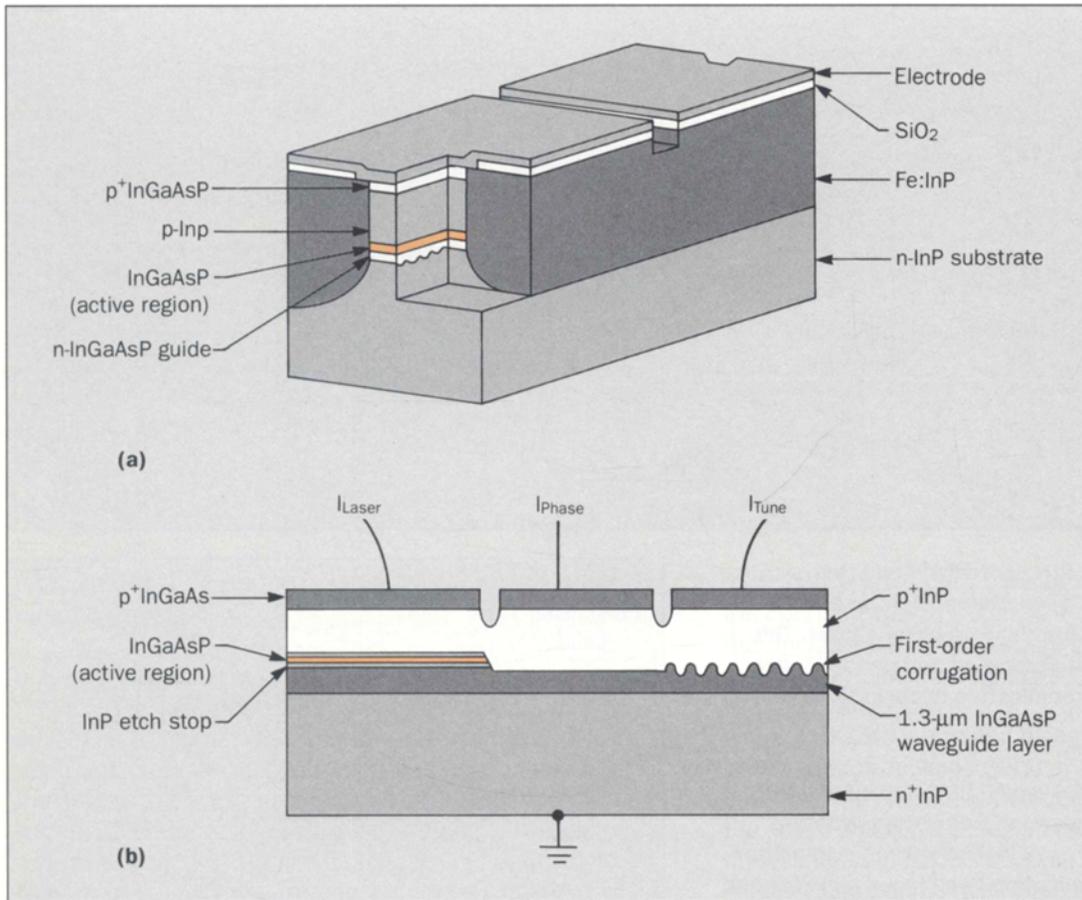
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Figure 7. Single wavelength laser structures for coherent transmission applications: (a) two-section distributed feedback laser and (b) three-section distributed Bragg reflector laser. These devices have adequate linewidth and tunability for a coherent frequency-shift-keying system.

Labels for (a): Electrode, SiO₂, Fe:InP, n-InP substrate, p⁺InGaAsP, p-Inp, InGaAsP (active region), n-InGaAsP guide

Labels for (b): I_{Laser}, I_{Phase}, I_{Tune}, p⁺InGaAs, InGaAsP (active region), InP etch stop, p⁺InP, First-order corrugation, 1.3-μm InGaAsP waveguide layer, n⁺InP

signal (at the receiver) into an electrical signal from which the original coded information is retrieved using a series of functions including amplification, equalization, filtering, and timing.

Two types of photodetectors are currently manufactured at AT&T: the positive-intrinsic-negative (PIN) photodiode and the avalanche photodiode (APD). The electrical signal in the APD is internally amplified by the probabilistic avalanche process, whereby the photogenerated carriers undergo multiplication. This makes the APD capable of detecting lower levels of optical signals than the PIN photodiode. Because the number of photons per bit of information decreases with increasing data rates for a given average incident power, APDs are needed for high-speed receivers that require the capability of detecting lower levels of optical signals.

Lightwave transmission systems operating near 1.3 μm and 1.55 μm use PIN photodiodes and APDs fabricated using the InGaAsP material system with an InGaAs-absorbing region. Figure 8 shows the structure of
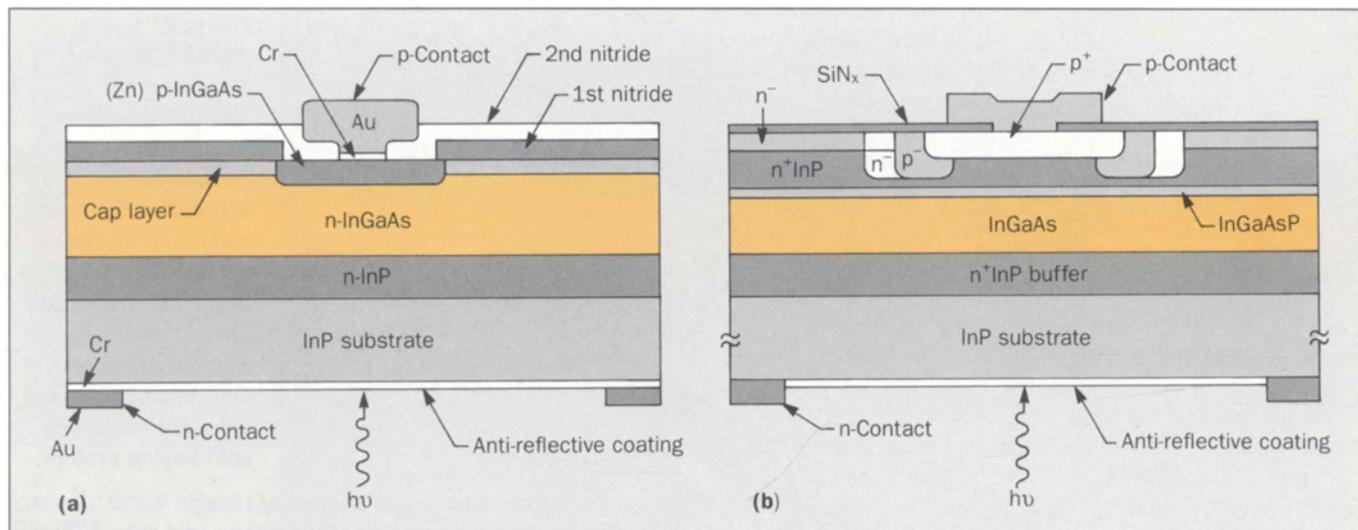
Figure 8. Schematic of (a) PIN photodiode and (b) avalanche photodiode (APD) structures. Light in both devices is absorbed by the low-doped n-InGaAs layer. The APD structure has separate absorption and multiplication regions (SAM-APD). The multiplication occurs in the n-InP layer.

Figure 9. Energy levels in (a) a bulk III-V semiconductor heterostructure and (b) a quantum-well heterostructure. When a photon is absorbed, an electron makes a transition from the valence to the conduction band in example (a) and from a low-energy level to a high-energy level within the conduction band in example (b).
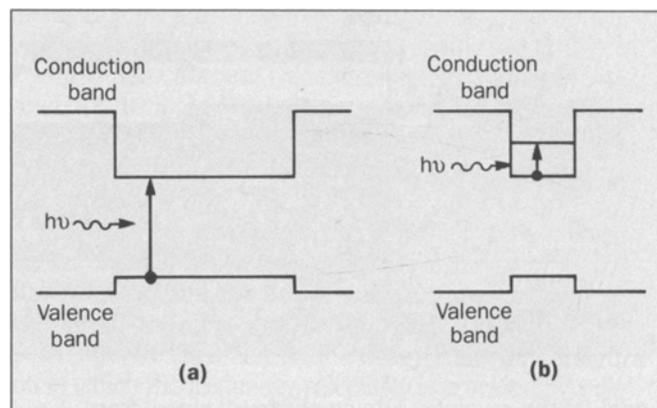
(a) the PIN photodiode and (b) the APD. The incident light is absorbed in the low-doped (10^{16}/cm^3) InGaAs layer, generating carriers that are collected by the external circuit.

      PIN photodiodes are easier to fabricate and are extensively used for low and moderate data-rate lightwave receivers. PIN photodiodes manufactured at AT&T have a reliability of one FIT (one failure in 10^9

hours) and are being used in the transatlantic fiber-optic cable transmission system (TAT-8).

      For APDs, the photogenerated carriers in the InGaAs layer undergo multiplication via impact ionization in the n-InP multiplication layer before collection at the external circuit. APDs have been fabricated that have gain-bandwidth products of 70 GHz and bandwidths greater than 6 GHz at a gain of 10. InGaAs APDs
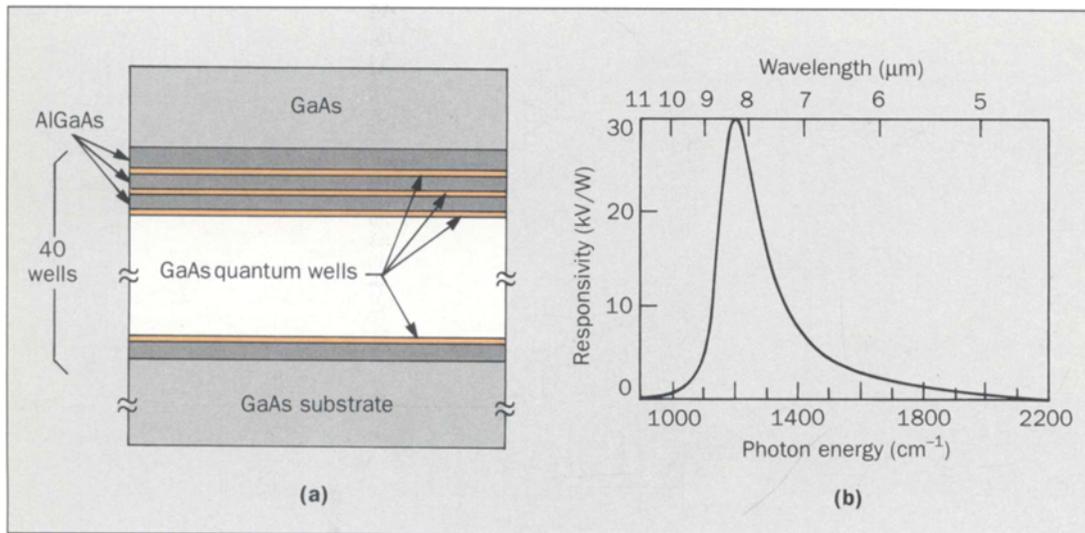
Figure 10. (a) Structure and (b) responsivity as a function of wavelength for a GaAs-AlGaAs superlattice photodiode.

fabricated at AT&T are used in the FT Series G transmission system.
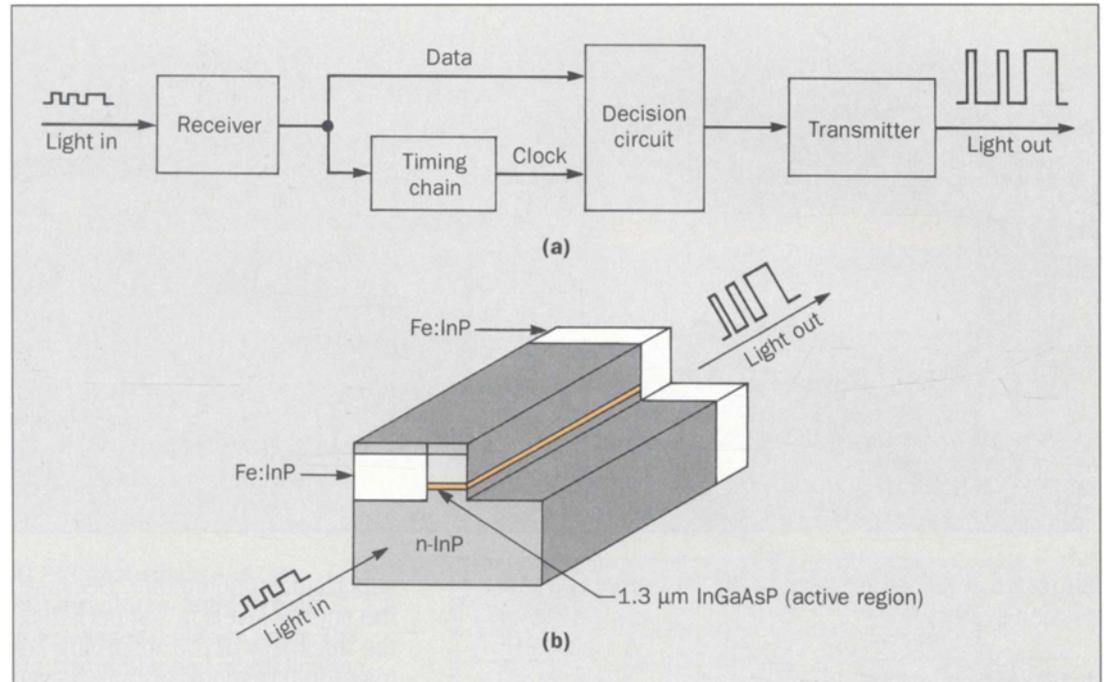
Quantum-Well Devices

The photodetectors described thus far rely on interband transitions for operation. A new class of photodetectors developed recently relies on intraband transitions in a superlattice structure for operation. In a superlattice photodiode with very-thin light-absorbing layers separated by higher bandgap semiconductors (quantum wells), quantum mechanical effects restrict the kinetic energy of electrons and holes to discrete values for velocities normal to the thin layer. This results in a discrete set of energy levels both in the conduction and valence bands (Figure 9). Superlattice photodetectors operate on the following principle. When an electron makes a transition from a low-energy level to a higher energy level in the conduction band, its probability of escape from the potential energy barrier increases. This generates a photocurrent or a change in conductivity that is observed using an external electrical circuit. Figure 10 shows the structure and responsivity of a GaAs-AlGaAs

superlattice photodiode. Because the separation between the energy levels in a superlattice structure depends on the thickness of the absorbing layers, the wavelength of maximum responsivity can be varied simply by changing the layer thicknesses.

Lasers fabricated using very-thin light-emitting layers (quantum-well lasers) also exhibit a change in emission wavelength with a change in the thickness of the active layer. These lasers exhibit lower spectral width under modulation than regular active-layer lasers, which makes them attractive as sources for direct-detection systems operating near the chromatic dispersion limit.

In a superlattice structure, the conduction and valence band edge discontinuities differ significantly from those of bulk materials, which can lead to a large difference in ionization rates of electrons (α) and holes (β). For a 50-layer AlGaAs/GaAs superlattice, the measured ratio of effective ionization rates of electrons and holes, α/β, is 8, compared to a value of 2 for bulk GaAs. A large α/β is needed for low-noise APDs. Thus, APDs fabricated with superlattice-absorbing layers can have less noise than conventional absorbing layer devices.

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(a)

(b)

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Optical Amplifiers

As a light signal travels through a fiber, it weakens and gets distorted. Regenerators are used to restore the original optical pulses. Figure 11a is a block diagram of a lightwave regenerator such as that used in the FT Series G system. Its main components are the optical receiver, optical transmitter, electronic timing, and decision circuits. Experiments at Bell Laboratories have shown that an optical amplifier can *nearly* restore the original optical pulses and thereby increase the transmission distance without using conventional regenerators.

An optical amplifier structure is very similar to that of a laser (Figures 4 and 5), with both facets having an antireflection coating to suppress laser oscillation. This also helps enhance the optical gain. Internal amplifier gains of greater than 30 dB have been achieved.

For practical amplifiers, the facet reflectivity must be very small (typically less than 10^{-4}). Figure 11b shows a modified amplifier structure that can tolerate a higher facet reflectivity ($\sim 10^{-2}$), which is achievable using the current technology. The amplifying layer in this device terminates before reaching the output facet, thereby reducing the coupling of the reflected light from the facet back into the amplifying layer. Because of its simplicity, an optical amplifier becomes an attractive alternative for future lightwave systems when compared to today's regenerators.

Integrated Structures

The regenerators in current lightwave systems use hybrid circuits in which the electronic functions are performed by silicon or GaAs circuits and the photonic
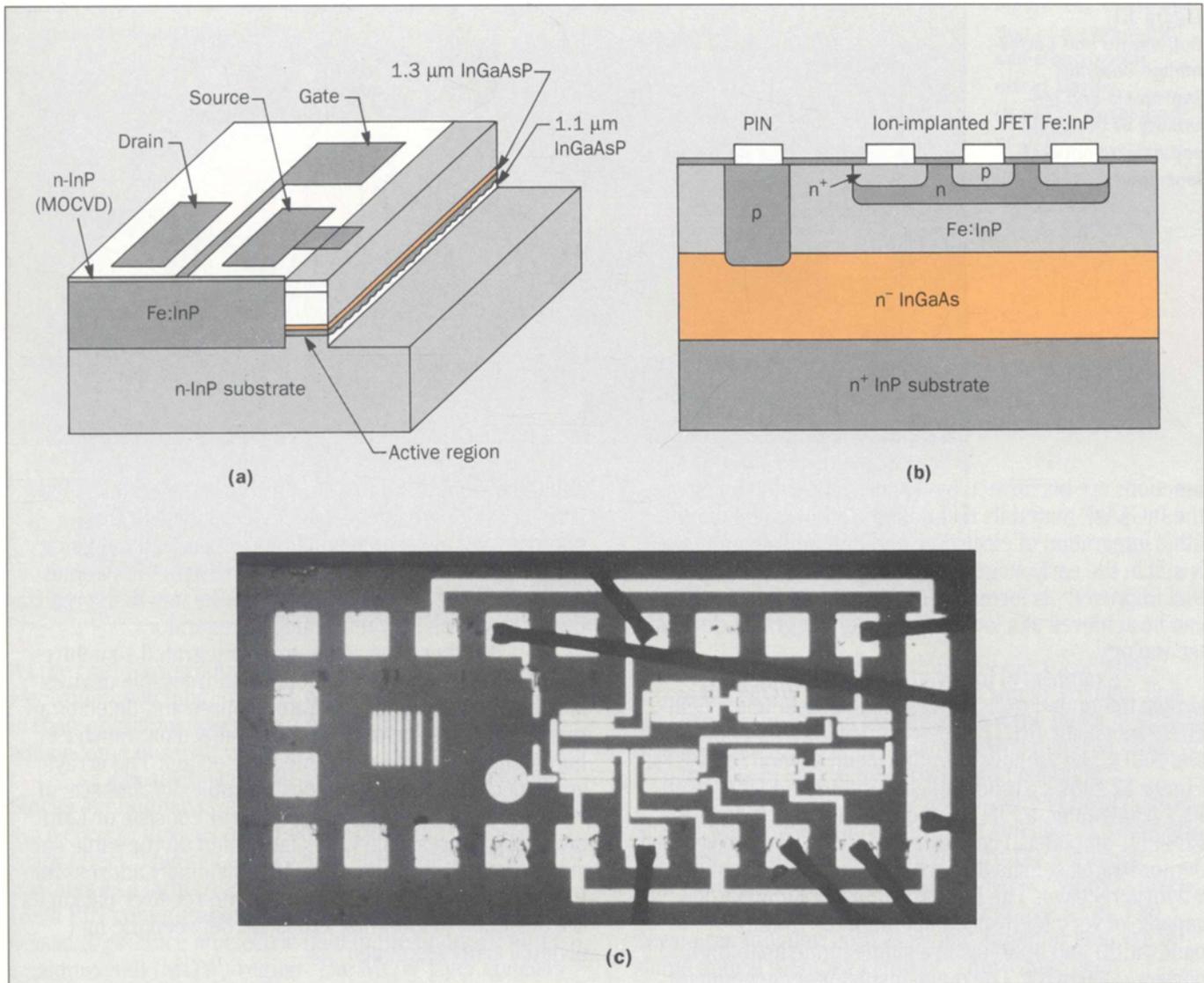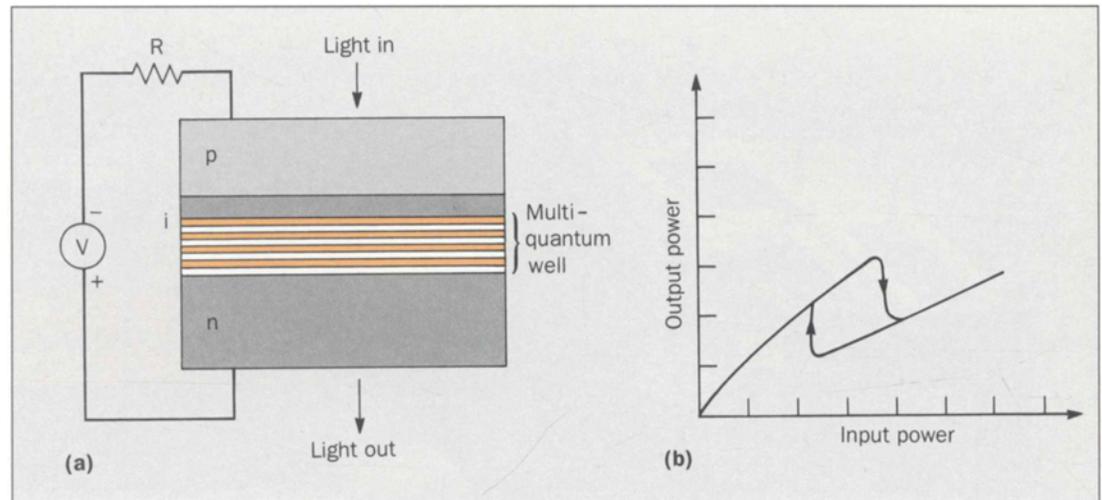
Figure 12. (a) A monolithically integrated DFB laser and MISFET; (b) an integrated PIN photodiode and junction-FET amplifier structure; and (c) a PIN-FET amplifier.

Figure 13.
Schematic and performance showing hysteresis and bistability of the basic self-electro-optic-effect device (SEED).

functions are performed by devices fabricated using the InGaAsP materials technology. Although the monolithic integration of electronic and photonic elements is still in the early stages of investigation, it is believed that improved performance and increased functionality can be achieved at a lower cost using integrated device technology.

Examples of integrated structures include: simple integrated transmitters using a laser and a field-effect transistor (FET), receivers using a PIN photodiode and FETs, and amplifier circuits using several InP FETs. Figure 12 shows a monolithically integrated DFB laser-FET transmitter, a PIN photodiode-FET receiver, and a PIN-FET amplifier. The integrated PIN-FET receiver has demonstrated sensitivities within a few decibels of that of a hybrid receiver. The laser structure in Figure 12a is capable of very high-speed operation (> 12-GHz bandwidth) and operates in a single mode up to high powers (> 30 mW). The metal-insulator-semiconductor field-effect transistor (MISFET) is fabricated on the low-doped n-InP layer. The goal of this work is to integrate the transmitter and receiver circuits with amplifier cir-

cuits that would lead to a single-chip regenerator. AT&T is also developing integrated devices in which the photonic and electronic functions are carried out using GaAs-based devices. Further development of materials and processing technologies will be the key to the realization of practical, fully integrated regenerators.

Another class of photonic integrated structures consists of an array of individually addressable devices fabricated on a single substrate.[1] Source and detector arrays of this type are suitable for parallel data transfer in high-density point-to-point interconnection. The arrays are expected to reduce the cost, complexity, and size of terminal equipment. The source array consists of 12 individually addressable LEDs fabricated on the same substrate; the detector array has 12 individually addressable PIN photodiodes. The transmitter and receiver packages are designed to minimize crosstalk between the individual array elements.

Photonic Switching

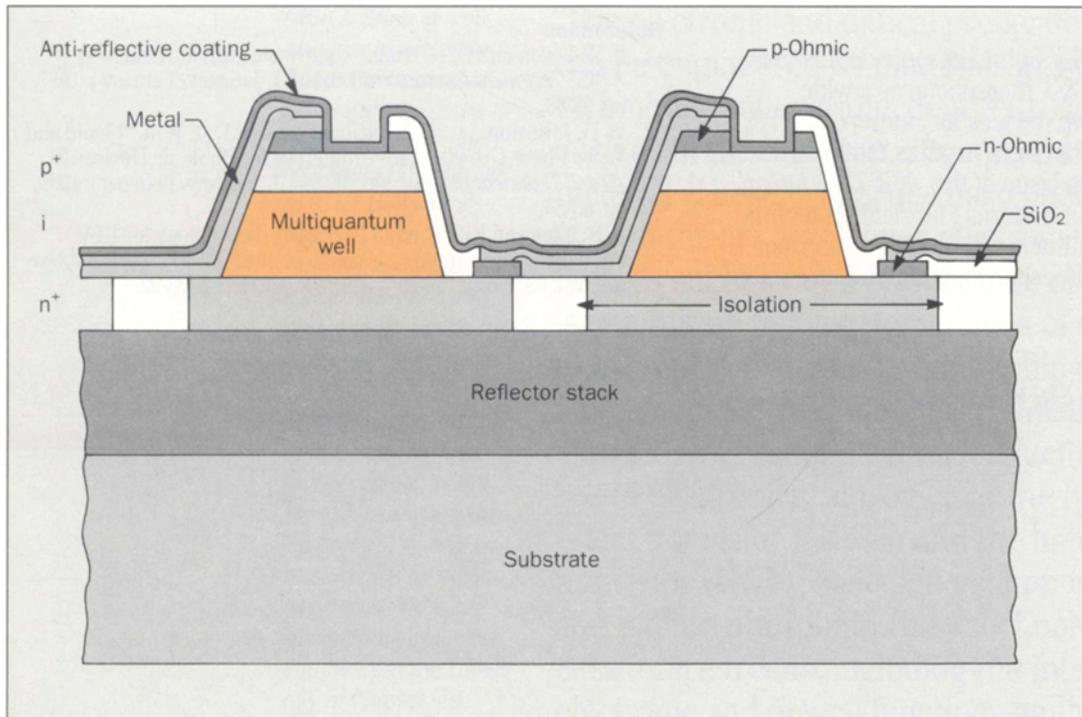In current lightwave transmission systems, switching and signal processing are done electronically.

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As the trend toward higher data rates continues, electronic switching systems will be pushed to the limits of their operating speeds and optical signal processing will become more attractive.

Optically bistable III-V devices are the building blocks of photonic switching systems. AT&T is developing a class of devices based on the quantum-confined Stark effect. This self-electro-optic-effect device (SEED) operates as a light-triggered optical switch. The device has a PIN configuration (Figure 13), which is reverse-biased to produce an electric field in the undoped multi-quantum-well (MQW) region. The MQW layer consists of thin layers (< 100Å) of alternating absorbing and non-absorbing regions. The incident light excites carriers in the absorbing regions, which changes the electrical im-pedance of the device (and, thus, the electrical field) across the MQW region for a given supply voltage. This field affects the optical transmission if the incident light is near the band edge of the quantum-well material. This, in turn, results in optical hysteresis and bistability.

A *symmetric* self-electro-optic-effect device (S-SEED) was developed recently that consists of two quantum-well PIN diodes in series (Figure 14). Unlike a conventional SEED device, this device is relatively insensitive to optical power fluctuations and bias level. The device can function both as a logic amplifier and as a bistable optical memory element. There have been demonstrations of arrays of these symmetric SEED devices with switching times in the range of a few nanoseconds.

Conclusion

A revolution in III-V optoelectronic device technology is taking place. AT&T manufactures a wide variety of reliable lightwave devices for numerous AT&T lightwave systems and subsystem product families. As the range of articles in this issue of the *AT&T Technical Journal* shows, advances in materials fabrication techniques have lead to semiconductors with tailored properties as well as new capabilities for discrete and integrated device fabrication.

Acknowledgments

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