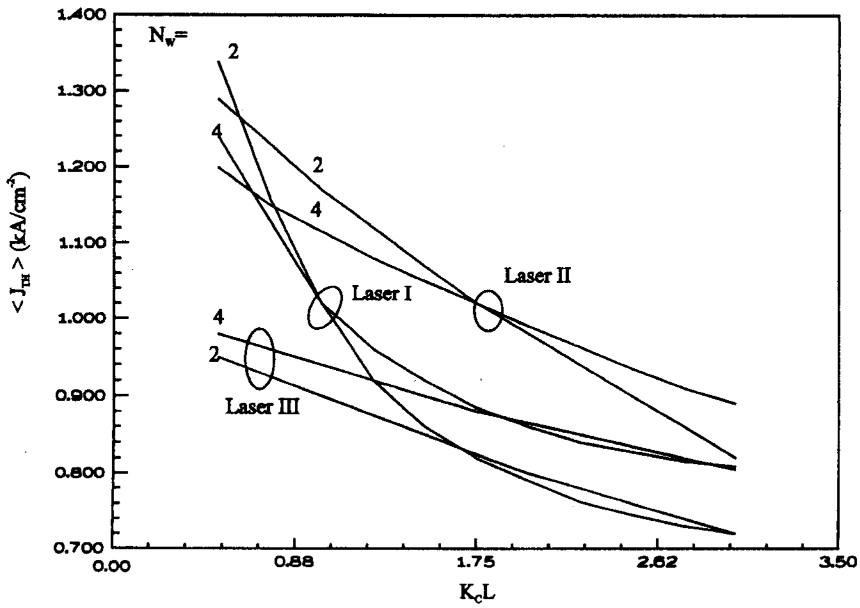

Figure 9 Average threshold current density versus coupling coefficient for Lasers I, II, and III in MQW structures with two and four wells

density a MQW transverse structure with four wells should be used. For higher coupling coefficients ($K_cL > 2$), a laser with two wells is always the most advantageous to decrease the threshold current density; Laser II ensures the best values for differential efficiency and gain selectivity.

REFERENCES

1. Y. Suematsu, "Long-Wavelength Optical Fiber Communications," *Proc. IEEE,* Vol. 71, 1983, pp. 692–721.
2. S. Adachi, "Material Parameters of $In_{1-x}Ga_xAS_yP_{1-y}$ and Related Binaries," *J. Appl. Phys.,* Vol. 53, No. 12, 1982, pp. 8775–8792.
3. A. L. Ribeiro, C. F. Fernandes, J. T. Pereira, and A. C. Serra, "Carrier and Radiation Confinement in a DFB Multiple Quantum Well Laser," *IEEE MELECON'94 Proceedings,* Catalog No. 94CH3388-6, 1994, pp. 564–567.
4. G. P. Agrawall and N. K. Dutta, *Long Wavelength Semiconductor Lasers,* Van Nostrand Reinhold, New York, 1986, Chaps. 3 and 9.
5. S. R. Chinn, P. S. Zory, and A. R. Reisinger, "A Model for GRIN-SCH-SQW Diode Lasers," *IEEE J. Quantum Electron.,* Vol. QE-24, No. 11, 1988, pp. 2191–2214.
6. N. K. Dutta, "Gain-Current Relation for $In_{0.72}Ga_{0.28}As_{0.6}P_{0.4}$ Lasers," *J. Appl. Phys.,* Vol. 52, No. 1, 1981, pp. 55–60.
7. A. Sugimura, "Band to Band Auger Effect in Long Wavelength Multinary III-V Alloy Semiconductor Lasers," *IEEE J. Quantum Electron.,* Vol. QE-18, No. 3, 1982, pp. 352–363.
8. C. F. Fernandes, "Mode Spectrum and Threshold Gain Calculations in DFB Lasers," *Microwave Opt. Technol. Lett.,* to be published.
9. H. Kogelnik and C. V. Shank, "Coupled-Wave Theory of Distributed Feedback Lasers," *J. Appl. Phys.,* Vol. 43, No. 5, 1972, pp. 2327–2335.
10. C. H. Henry, "Performance of Distributed Feedback Lasers Designed to Favor the Energy Gap Mode," *IEEE J. Quantum Electron.,* Vol. QE-21, No. 12, 1985, pp. 1913–1918.

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AN OPTICAL PULSE MODULATOR BASED ON AN ALL-FIBER MIRROR

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KEY TERMS

Fiber optics, all-fiber mirrors, optical modulators

ABSTRACT

In this article we present an all-fiber Sagnac interferometer modulated in a pulsed regime. It is demonstrated that a phase step applied in one extreme of the fiber loop, combined with the right polarization changes in the loop, can generate different types of pulses at the output of the interferometer. The pulse widths are determined by the transit time of the light through the fiber loop. Our present experimental arrangement can generate positive and negative 200-ns optical pulses. © 1996 John Wiley & Sons, Inc.

INTRODUCTION

A number of fiber-compatible devices are based on Sagnac interferometers formed by a loop of optical fiber at the output arms of a directional coupler. Sagnac reflectors have found applications as mirrors for optical-fiber lasers [1], gyroscopes [2], soliton filtering [3], Brillouin scattering observation [4], and sensors [5]. Fiber mirrors can be modulated by varying either the polarization state in the fiber loop [6] or the phase difference of the interfering beams [7, 8]. An electro-optic cristal can be inserted in the fiber loop as phase modulator [6, 7], or, alternatively, an external modulator (usually a piezoelectric ceramic) can be used [8].

Unlike other sorts of fiber interferometers, which can be efficiently modulated from dc to microwave frequencies [9], Sagnac interferometers are difficult to modulate because the interfering beams propagate through the same fiber. Modulating by means of a slow phase modulator working in the kilohertz range would require a delay line several kilometers long in the loop of the mirror. This length of fiber, apart from being excessive for practical purpose, will constrain the applications to the low-loss telecommunication windows. The length of the delay line in the loop of the mirror can be reduced to tens of meters by using a faster phase modulator [10]; consequently, reflectors operating in the visible and near-infrared areas of the spectrum can be efficiently modulated at frequencies of megahertz.

In this article we demonstrate an all-fiber Sagnac interferometer modulated in a pulsed regime. Pulses are generated by shifting, with a step function, the phase difference between the signals propagating in opposite directions in the fiber loop. The output of the interferometer switches from a stable state to a metastable state when a discontinuous variation of the path length is introduced in one end of the fiber loop. The mirror stays in the metastable state during a time interval determined by the time delay between the counterpropagating signals. Negative or positive pulses can be generated by arranging the polarization state of the light traveling in the mirror. Our present arrangement can generate 200-ns positive and negative optical pulses and gives the key to extend this technique to the 10–1000-ns range. The nonideal behavior of the piezoelectric ceramic used as phase shifter has been also theoretically analyzed.

THEORY

The basic reason to use an all-fiber mirror as an optical modulator is to induce a phase difference, $\Delta\Phi(t)$, between the waves traveling in opposite directions in the loop, in our case by generating a phase modulation $\Phi(t)$ in one extreme of the loop and taking advantage of the delay time τ with respect the other extreme:

$$\Delta\Phi(t) = \Phi(t) - \Phi(t-\tau). \tag{1}$$

This basic idea multiplies its versatility, giving rise to a new set of configurations, when it is combined with an overall birefringence in the loop.

We have carried out the analysis with Jones calculus to describe the amplitude and the polarization state of the signal along the single-mode fiber. The input and output signals in a birefrigent fiber can be related by a Jones matrix as

$$\mathbf{E}_o = fe^{j\Phi}\begin{pmatrix} \cos\Gamma\, e^{j\mu} & j\sin\Gamma \\ j\sin\Gamma & \cos\Gamma\, e^{-j\mu} \end{pmatrix}\mathbf{E}_i, \tag{2}$$

where f and Φ are the fiber attenuation and the phase variation, and the parameters Γ and μ describe the fiber birefringence. With the nomenclature shown in Figure 1, the relations between the input and output signals in the fiber loop are

$$\mathbf{E}_{o4} = fe^{j\Phi(t)}\begin{pmatrix} -\cos\Gamma\, e^{j\mu} & j\sin\Gamma \\ -j\sin\Gamma & \cos\Gamma\, e^{-j\mu} \end{pmatrix}\mathbf{E}_{i3}, \tag{3}$$

$$\mathbf{E}_{o3} = fe^{j\Phi(t-\tau)}\begin{pmatrix} -\cos\Gamma\, e^{j\mu} & -j\sin\Gamma \\ j\sin\Gamma & \cos\Gamma\, e^{-j\mu} \end{pmatrix}\mathbf{E}_{i4}. \tag{4}$$

These equations take into account the reflection of one of the components of the Jones vector when the fiber bends to close the loop.

The relations between the input and output signals in a polarization-independent coupler are

$$\mathbf{E}_{i3} = \alpha t\mathbf{E}_{i1}, \qquad \mathbf{E}_{i4} = jt\sqrt{1-\alpha^2}\,\mathbf{E}_{i1}, \tag{5}$$

$$\mathbf{E}_{o1} = \alpha t\mathbf{E}_{o3} + jt\sqrt{1-\alpha^2}\,\mathbf{E}_{o4}$$
$$\mathbf{E}_{o2} = jt\sqrt{1-\alpha^2}\,\mathbf{E}_{o3} + \alpha t\mathbf{E}_{o4}, \tag{6}$$

where α is the coupling coefficient and t the transmission coefficient.

Assuming an input light with a Jones vector:

$$\mathbf{E}_{i1} = \begin{pmatrix} \sqrt{P}\,e^{j\delta} \\ \sqrt{1-P} \end{pmatrix}, \qquad \text{with } 0 \le P \le 1, \qquad 0 \le \delta \le \pi, \tag{7}$$

and substituting Eqs. (3) and (4) in (5) and (6), the transmission coefficient T of the Sagnac interferometer can be expressed as a function of the fiber birefringence and the phase difference between the counterpropagating signals:

$$T = t^4f^2\big(1 - 2\alpha^2\sqrt{1-\alpha^2}\,(1 + \cos(2\Gamma)\cos(\Delta\Phi) + \sin\chi\,\sin(2\Gamma)\sin(\Delta\Phi))\big), \tag{8}$$

where χ is a parameter defined as $\sin\chi \equiv 2\sqrt{P(1-P)}\,\cos(\delta+\mu)$.

We can point out some characteristics of the transmission T given by the expression (8). In the general case, the transmission depends on the input polarization state, because the factor $\sin\chi$ depends on P and δ, although this dependence is canceled when $\Delta\Phi = 0$ or $2\Gamma = 0$, allowing for the all-fiber mirror to resume the standard behavior. The case $\Delta\Phi = 0$ corresponds in our case to a static operation of the system, and the case $2\Gamma = 0$ corresponds to a null polarization change of the light in the loop of fiber.

The combination of the factors determined by $\Delta\Phi$ and 2Γ is the key to developing the modulation technique presented in this article. For optimum amplitude modulation a coupler with 50% splitting ratio and a lossless system are required. We focus on two cases: the generation of positive transmission pulses and the generation of negative transmission pulses. In the first case, before generating any phase modulation, that is, when $\Delta\Phi = 0$, 2Γ has to be adjusted to give the minimum transmission $T = 0$, which corresponds to $2\Gamma = 0$. In the second case, 2Γ has to be adjusted to give the maximum transmission $T = 1$, which corresponds to $2\Gamma = \pi$. Thus, once the static adjustments of Γ have been performed, the generation of a time-dependent phase difference $\Delta\Phi(t)$ can be used to modulate the transmission:

$$T = \tfrac{1}{2}(1 \pm \cos\Delta\Phi(t)), \tag{9}$$

where the minus sign corresponds to the generation of positive transmission pulses and the plus sign to negative transmission pulses. The ideal modulation would be obtained, for example, by generating a phase step of π rad at $t = 0$ in one extreme of the loop, which according to Eqs. (1) and (9) would give rise to a square pulse whose width is determined by the delay time τ:

$$T = U(t) - U(t-\tau), \qquad \text{for positive pulses}, \tag{10a}$$
$$T = 1 - (U(t) - U(t-\tau)), \qquad \text{for negative pulses}, \tag{10b}$$

where $U(t)$ is the unitary step function.

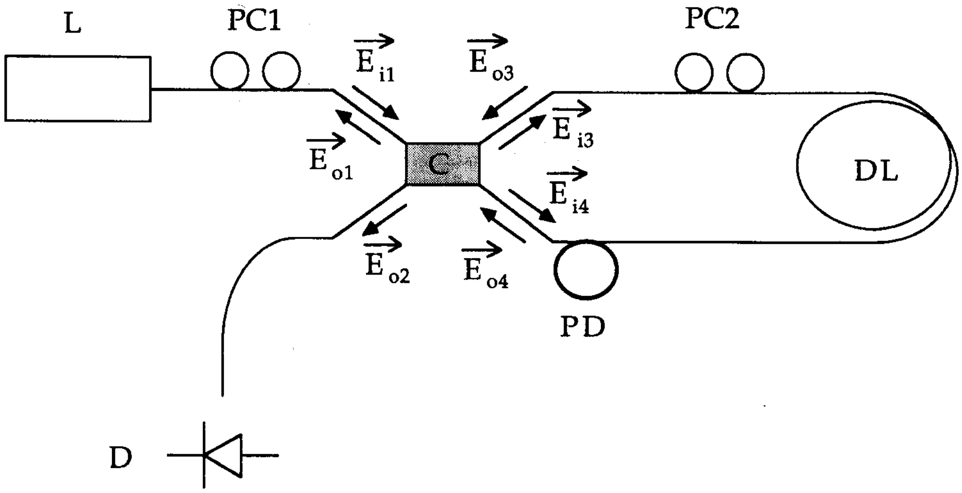

Figure 1 Experimental arrangement. L, laser; PC1 and PC2, polarization controllers; C, coupler; D, detector; DL, delay line; PT, piezoelectric tube, E_{im} and E_{om}: input and output signals at arms number m of the coupler

EXPERIMENTAL RESULTS AND DISCUSSION

The experimental arrangement that we have set up to demonstrate the feasibility of a pulse generator based on an all-fiber mirror uses an HeNe laser (633 nm) and a standard 50:50 coupler. The phase modulator consisted of a piezoelectric tube of 50-mm diameter and 1-mm wall thickness. About 1.5 m of fiber was wound around the tube, at one end of the loop. The wall thickness of the piezoelectric tube determines a nominal frequency of resonance Ω of 2 MHz. Thus, if we apply a voltage step to generate a phase modulation in the light guided by the fiber, the maximum rate of phase change will be determined by the value of Ω. Therefore, we design the loop to have a delay time $\tau = \pi/\Omega$; that is, τ equal to a half period, which corresponds to about 50 m of fiber in our case. In fact, $\tau = \pi/\Omega$ is the optimum if we are interested in a harmonic phase modulation [8, 10].

When a voltage step is applied to a piezoelectric tube it produces a step phase shift perturbed by the transitory response of the piezoelectric. The perturbation from the ideal response appears because the piezoelectric tube behaves as a resonant circuit with a frequency of resonance Ω and a quality factor Q. If we assume that the piezoelectric produces a phase variation proportional to the electric charge of the equivalent capacitor, then the phase change generated by a voltage step applied at $t = t_0$ has the expression

$$\Phi_S(t, t_0) = \Phi_\infty\left\{\left[\cos(\Omega(t - t_0)) + \frac{\sin(\Omega(t - t_0))}{2Q}\right] \times \exp\left(-\frac{\Omega(t - t_0)}{2Q}\right) - 1\right\}U(t - t_0), \quad (11)$$

where Φ_∞ is the stationary phase change. The phase modulation generated by a voltage pulse with a width Δ is given by

$$\Phi(t) = \Phi_S(t, t_0) - \Phi_S(t, t_0 + \Delta). \quad (12)$$

Finally, Eq. (1) determines $\Delta\Phi(t)$ and Eq. (8) the transmission. By applying a harmonic voltage we have measured the value of Ω for our phase modulator, obtaining $\Omega = 2.15$ MHz, as well as the quality factor $Q = 4$.

Figure 2(a) shows the transmission obtained when a step voltage is applied to the piezoelectric tube, and Figure 2(b) is the corresponding theoretical calculation. We can see a main pulse followed by a dumped oscillation. The half-power pulse width is 200 ns, which is in good agreement with the time delay of the fiber loop. The dumped oscillation is caused by the oscillating response of the piezoelectric tube before it reaches its steady state.

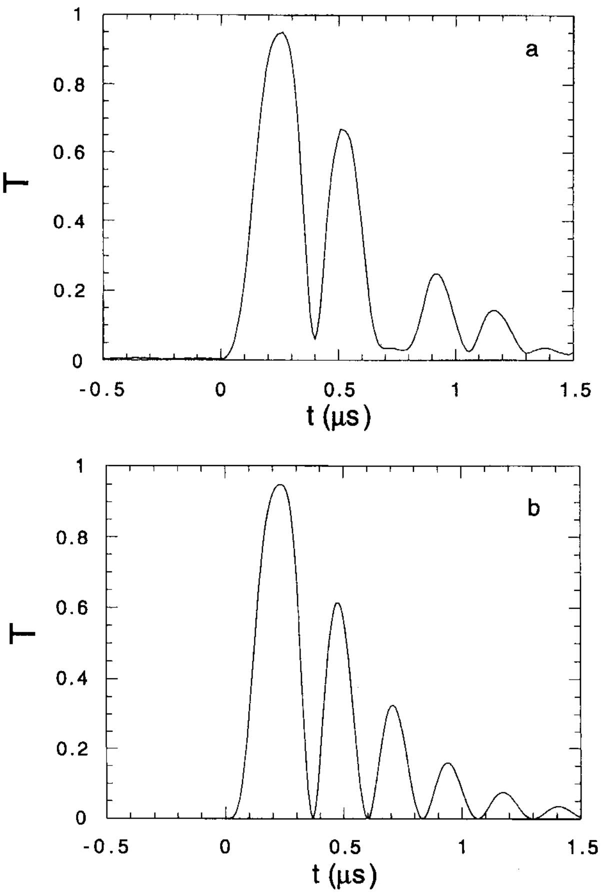

Figure 2 Transmission as a function of time when a voltage step is applied to the piezoelectric tube and the polarization controller in the loop is adjusted to give the minimum stationary transmission: (a) experiment, (b) theory

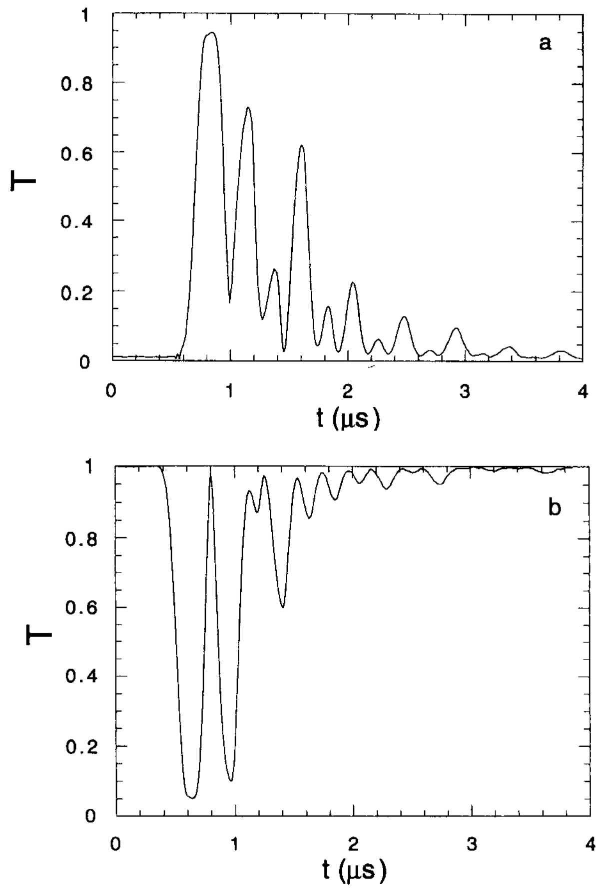

Figure 3 Experimental transmission as a function of time when a voltage pulse of 400-ns width is applied to the piezoelectric tube. The polarization controller in the loop is adjusted to give (a) the minimum stationary transmission, and (b) the maximum stationary transmission

Figure 3 gives two examples of positive and negative pulses, obtained when a 400-ns voltage pulse is applied to the piezoelectric tube. In Figure 3 we can see the important role that the polarization plays in this modulation technique, because the only difference between Figures 3(a) and 3(b) is a different adjustment of the polarization controllers. In this case the piezoelectric generates two transitories, each one caused by one of the ramps of the driving voltage. We can see the corresponding main pulses in Figure 3(b). In this case the second pulse is perturbed by the secondary peaks of the first one, because the width of the excitation signal is shorter than the relaxation time of the piezoelectric tube.

CONCLUSIONS

The reliability of a new modulation technique has been demonstrated with an all-fiber mirror made of a loop of 50 m of optical fiber with 2-MHz piezoelectric tube used as a phase modulator. The transmission can be modulated either to give positive optical pulses or negative pulses of 200-ns width. An advantage of this technique is that it gives rise to a single-mode optical-fiber component that can be combined to construct in-line all-fiber systems. The technique can be extended to generate pulses in the 10–1000-ns range.

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REFERENCES

1. I. D. Miller, D. B. Mortimore, P. Urquhart, B. J. Ainslie, S. P. Craig, C. A. Millar, and D. B. Payne, "A Nd^{3+}-doped cw Fibre Laser Using All-Fibre Reflectors," *Appl. Opt.*, Vol. 26, 1987, pp. 2197–2201.
2. S. K. Kim, H. K. Kim, and B. Y. Kim, "Er^{3+}-Doped Fibre Ring Laser for Gyroscope Applications," *Opt. Lett.*, Vol. 19, No. 22, 1994, pp. 1810–1812.
3. K. Rottwitt, W. Margulis, and J. R. Taylor, "Spectral Filtering of Solitons by Means of a Nonlinear Amplifying Loop Mirror," *Opt. Lett.*, Vol. 20, No. 15, 1995, pp. 1601–1603.
4. N. Nishizawa, S. Kume, M. Mori, and T. Goto, "Symmetric and Asymmetric Fibre Loop Mirrors for Observing Guided-Acoustic-Wave Brillouin Scattering in Polarization-Maintaining Fibres," *Opt. Lett.*, Vol. 19, No. 18, 1994, pp. 1424–1426.
5. R. T. de Carvallo and J. Blake, "The Sagnac Interferometer as a Two-Parameter Sensor," *J. Lightwave Technol.*, Vol. 13, No. 7, 1995, pp. 1250–1255.
6. A. Yu and A. S. Siddiqui, "Optical Modulators Using Fibreoptic Sagnac Interferometers," *IEE Proc.-Optoelectron.*, Vol. 141, No. 1, 1994.
7. N. A. Whitaker, Jr., R. J. Lustberg, M. C. Gabriel, and H. Avramopoulos, "Low-Drift Modulator without Feedback," *IEEE Photon. Technol. Lett.*, Vol. PTL-4, 1992, pp. 855–857.
8. R. A. Bergh, H. C. Lefevre, and H. J. Shaw, "All-Single-Mode Fibre-Optic Gyroscope with Long-Term Stability," *Opt. Lett.*, Vol. 6, 1981, pp. 502–504.
9. J. L. Cruz, J. Marzal, and M. V. Andrés, "An All-Fiber RF Modulation Technique: Frequency Response Calibration of Optical Detectors," *IEEE Trans. Microwave Theory Tech.*, Vol. MTT-43, No. 9, 1995, pp. 2361–2363.
10. J. L. Cruz and M. V. Andrés, "Dynamic Path Length Changes in All-Fibre Mirrors: Transmission Modulation," *Fibre Integrated Opt.*, Vol. 14, 1995, pp. 295–302.

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A CONDUCTOR-BACKED UNIAXIAL SLAB AS A POLARIZATION TRANSFORMER

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KEY TERMS
Polarization transformers, uniaxial slabs, electromagnetics, wave propagation

ABSTRACT

In this article the polarization properties of a field reflected from a conductor-backed uniaxial slab are considered. The incident field is propagating normally into the interface of the uniaxial slab and is reflected from it. The polarization of the field is changed in reflection. By choosing the thickness of the slab properly, the linearly polarized incident field can be transformed to any polarization in reflection. The polarization state can be adjusted by rotating the slab. Also, by choosing the material parameters properly, the polarization-transforming effect occurs in a wide frequency range. © 1996 John Wiley & Sons, Inc.