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PULSE PROPAGATION IN INHOMOGENEOUS OPTICAL WAVEGUIDES

Final Report

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Curtis R. Menyuk
Department of Electrical Engineering
University of Maryland
Baltimore, MD 21228-5398

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PULSE PROPAGATION IN INHOMOGENEOUS OPTICAL WAVEGUIDES

I. Summary of Accomplishments in 1992-1996

During the period of our grant "Pulse propagation in inhomogeneous optical waveguides," we can point with pride to a strong record of accomplishment. These accomplishments include two Ph.D. dissertations, twenty-six archival journal publications that have appeared in print, six articles that have appeared in conference or summer school proceedings, sixteen regular conference presentations, and eleven invited conference presentations. A complete record of our publications and presentations may be found in Sec. II.E. Far more important than the quantity of publications, however, is the impact of our work on the scientific and engineering communities. One measure of our impact is that we have been invited to give talks at major meetings as diverse as the ACOFT '94 meeting in Melbourne, Australia which serves communication engineers that are responsible for developing long-haul communication systems and the SIAM conference on Applications of Dynamical Systems that primarily serves applied mathematicians. Another measure is that Dr. Menyuk was invited by the Undersea Lightwave Implementation Department at AT&T Bell Laboratories to prepare a mini-course entitled "Nonlinear Fiber Optics in a Long-Distance Transmission" that has also been presented at other government and university laboratories. Members of Dr. Menyuk's research group continue to be in demand as speakers at a variety of meetings and schools.

The areas in which we have been working — randomly varying optical fiber birefringence, passively modelocked lasers, and quasi-phase matched second harmonic generation — are all still of great current interest. Recent progress in soliton transmission has been nothing short of outstanding with the recent achievement of single channel 15 Gbit/sec, nearly error-free transmission over 35,000 km.¹ At the same time, remarkable progress with the presently used NRZ (non-return-to-zero) transmission mode makes it less clear that solitons will ultimately be used. Eight channel transmission at 5 Gbit/sec per channel over 8,000 km has been demonstrated.² In both cases, it is apparent that randomly varying birefringence coupled with the fiber nonlinearity and dispersion plays a key role in inducing errors during long-distance transmission.^{3,4} Passively modelocked fiber lasers have also made significant progress. Both fiber figure-8 and fiber ring lasers have produced pulses that are under 100 fs in duration.^{5,6} Finally, quasi-phase-matched waveguides for the production of blue-green light have also made important progress. Integrated packages that produce 2–3 mW of blue-green light have recently been prototyped.⁷ These sources of blue-green light have important potential applications to data storage, and, in particular, should increase the capacity of CD recordings by a factor of 4–5.

We have contributed in important respects to all these areas. In long-distance transmission systems, the length scale on which the birefringence varies randomly (30–100 m)

is short compared to the nonlinear and dispersive scale lengths (100–1000 km).⁸ Consequently, it is crucial to understand and characterize this randomly varying birefringence when studying long-distance evolution in optical fibers. We have done that in a series of studies^{9–12} that has also led us to propose a numerical scheme for modeling these systems that should be orders of magnitude faster than the schemes presently being used. In our studies of the fiber ring and figure-8 lasers, we proposed that nonlinear polarization rotation is the mechanism responsible for fast saturable absorption in the fiber ring lasers¹³ — a result that was later verified experimentally.¹⁴ We also explored a new approach to determining the conditions for modelocking and self-starting in these lasers that uses the computer to determine the linear stability of both the pulsed and cw solutions.^{15,16} Our work on quasi-phase-matched waveguides has been delayed because the opportunity arose to collaborate with experimentalists at the Army Research Laboratory on the study of electrostatically induced waveguides. In this innovative approach to switching, the waveguide configuration is altered by external voltages. We showed that the loss plays a crucial role in determining the crosstalk¹⁷ and that by changing the voltage, these switches can be tuned over 400 nm.¹⁸ Despite this delay, we have developed an innovative transfer matrix approach that allows us to calculate the Bloch modes in the segmented, quasi-phase-matched waveguides that are being used by the Du Pont Experimental Station.¹⁹

In all this work, we have worked closely with leading experimentalists and their groups. These include Linn Mollenauer at AT&T Bell Laboratories on our studies of long-distance fiber transmission, Irl Duling at the Naval Research Laboratory on our studies of fiber lasers, George Simonis and T.-C. Huang of the Army Research Laboratory on our study of electrostatically induced waveguides, and John Bierlein of the Du Pont Experimental Station on our studies of quasi-phase-matched waveguides.

Additionally, we have made important progress on fundamental studies of soliton robustness,^{20,21} and we helped elucidate the behavior of $\chi^{(2)}$ cascaded solitons in collaboration with the experimental group of George Stegeman^{22–25} at the University of Central Florida. We have also explored the use of acceleration techniques in our waveguide codes, and we have greatly improved our graphics capabilities, culminating in the direct computer display of the mini-course that we presented at AT&T Bell Laboratories.

In Section II of this report, we describe in more detail some of our specific accomplishments.

II. Detailed Accomplishments

Our work has focused on the effects of randomly varying birefringence in long-distance communication systems, stability of passively modelocked fiber lasers, and on the simulation of solid state waveguides. We have also carried out fundamental studies of soliton robustness, $\chi^{(2)}$ solitons, and we have developed the use of direct, computer-generated graphics in our presentations. We discuss all these topics sequentially.

A. Randomly Varying Birefringence in Long-Distance Communication Systems

The starting point for our studies was the observation that the birefringence in optical fibers should be considered large and rapidly varying. Under these circumstances, both we⁸ and Evangelides, *et al.*²⁶ showed that the basic equations that describe evolution in birefringent optical fibers

$$\begin{aligned} i\frac{\partial u}{\partial z} + i\delta\frac{\partial u}{\partial t} + \frac{1}{2}\frac{\partial^2 u}{\partial t^2} + \left(|u|^2 + \frac{2}{3}|v|^2\right) + \frac{1}{3}u^*v^2 \exp(-iR\delta z) &= 0, \\ i\frac{\partial v}{\partial z} - i\delta\frac{\partial v}{\partial t} + \frac{1}{2}\frac{\partial^2 v}{\partial t^2} + \left(\frac{2}{3}|u|^2 + |v|^2\right) + \frac{1}{3}u^2v^* \exp(iR\delta z) &= 0, \end{aligned} \quad (\text{II.A.1})$$

reduces to the Manakov equation

$$\begin{aligned} i\frac{\partial u}{\partial z} + \frac{1}{2}\frac{\partial^2 u}{\partial t^2} + (|u|^2 + |v|^2)u &= 0, \\ i\frac{\partial v}{\partial z} + \frac{1}{2}\frac{\partial^2 v}{\partial t^2} + (|u|^2 + |v|^2)v &= 0, \end{aligned} \quad (\text{II.A.2})$$

after appropriate averaging over the large and rapid variations, where u and v are the complex wave envelopes in orthogonal polarizations, z and t are normalized distance and time, δ is the group velocity difference, and $R\delta$ is the inverse beat length. To obtain, Eq. (II.A.2), it was assumed that the electric field randomizes on the Poincaré sphere at regular intervals. It is not obvious that this assumption is valid. Linearly, it had long been known that the rapidly and randomly varying birefringence leads to pulse spreading,²⁷ referred to as polarization mode dispersion. While theoretical work had been carried out which successfully predicted the parametric dependence of the polarization mode dispersion and the pulse arrival times,²⁸⁻³⁰ this work was based on the assumption that the birefringence axes are nearly fixed, albeit rapidly varying. This assumption is known to be untrue.

We undertook a careful re-examination of these questions, and we have completely resolved them. We have shown that the polarization mode dispersion has the same parametric form almost regardless of the physical variation of the birefringence, as long as it is sufficiently random. We have also calculated the polarization decorrelation and diffusion lengths, and we have shown that while they may vary widely, Eq. (II.A.2) is always

valid. However, the higher order corrections are strongly effected by the detailed physical behavior.

Optical fibers are linearly birefringent so that the wave evolution is described by the equation

$$\frac{d}{dz} \begin{pmatrix} A_1 \\ A_2 \end{pmatrix} = ib \begin{pmatrix} \cos \theta & \sin \theta \\ \sin \theta & -\cos \theta \end{pmatrix} \begin{pmatrix} A_1 \\ A_2 \end{pmatrix}, \quad (\text{II.A.3})$$

where A_1 and A_2 are the envelopes of the two polarizations, b is proportional to the birefringence strength, and θ gives the orientation of the axes of birefringence. Making the transformation that would diagonalize Eq. (II.A.3) in the absence of θ -variations, we find

$$\frac{d}{dz} \begin{pmatrix} B_1 \\ B_2 \end{pmatrix} = \begin{pmatrix} ib & \theta_z/2 \\ \theta_z/2 & -ib \end{pmatrix} \begin{pmatrix} B_1 \\ B_2 \end{pmatrix}, \quad (\text{II.A.4})$$

where B_1 and B_2 are the transformed envelopes and $\theta_z \equiv d\theta/dz$. Regardless of how θ varies, Eq. (II.A.4) looks like the model with nearly fixed birefringence. This simple observation is at the root of the demonstration that the parametric behavior of the polarization mode dispersion is always the same if the birefringence variation is sufficiently random.⁹ We also demonstrated an ergodic theorem.⁹ To make further progress, we considered two specific models. In the first, we allowed θ in Eq. (II.A.3) to vary arbitrarily while keeping b fixed; in the second, we allowed $b \cos \theta$ and $b \sin \theta$ to vary in accordance with a bi-Maxwellian distribution. We then carried out a series of Monte Carlo simulations in which we solved Eq. (II.A.3) starting with the initial condition $(S_1, S_2, S_3) = (1, 0, 0)$, where S_1 , S_2 , and S_3 are the usual Stokes parameters, which can be done with no loss of generality. We determined $\langle S_1 \rangle$, $\langle S_1^2 \rangle$, $\langle S_2^2 \rangle$, and $\langle S_3^2 \rangle$.^{10,11} The first yields the rate at which the polarization decorrelates, while the latter three yield the diffusion rate on the Poincaré sphere. These diffusion lengths are different in general, so the assumption that there is a single scrambling length is not valid. Later, using the method of stochastic differential equations, we were able to calculate the polarization decorrelation and diffusion analytically for the first model,¹² and we obtained results that agreed with the simulations. We also derived the implications for the nonlinear evolution.¹² We showed that Eq. (II.A.2) still applies on a length scale that is much longer than the longest diffusion or decorrelation scale length. However, the behavior of the higher order contributions that lead, for example, to soliton depolarization⁸ depend critically on the different length scales.¹²

We note that these results are just as important for NRZ (non-return-to-zero) communication systems as they are for soliton systems.

B. Passively Modelocked Fiber Lasers

Our investigations of passively modelocked fiber lasers began with a theoretical investigation of a fiber ring laser that was designed by Mollenauer.³¹ When we originally simulated the startup of this laser, we were never able to obtain stable pulses because the original design had neither an explicit frequency limiter nor an explicit fast saturable

absorber, and a passively modelocked laser cannot operate stably without both these elements. We speculated that the fast saturable absorption came about because of the combination of nonlinear polarization rotation and polarization-selective elements.¹³ This hypothesis was later verified experimentally,¹⁴ and this physical understanding played an important role in the achievement of sub-100 fs pulses.⁵

From this point, we began a study of the stability of passively modelocked lasers using as our starting point the model equation³²

$$\frac{\partial U}{\partial z} = (g - l + i\theta)U + (B + iD)\frac{\partial^2 U}{\partial t^2} + (\Gamma + iK)|U|^2U = 0, \quad (\text{II.B.1})$$

where U is the complex pulse envelope, z indicates the number of passes through the laser system, t is time, g , l , and θ are gain, loss, and phase change, B and D account for a frequency limiter and dispersion, and finally Γ and K account for the fast, saturable absorber and Kerr nonlinearity. Equation (II.B.1) has the equilibrium solution

$$U_0 = A \text{sech}^{1+i\beta}(t/\tau) \exp(i\psi z), \quad (\text{II.B.2})$$

where A , τ , β , and ψ are determined from the laser parameters, g , l , θ , B , D , Γ , and K . Eq. (II.B.1) is closely related to the Ginzburg-Landau equation. The only distinction is that while all the parameters are constant in the Ginzburg-Landau equation, in Eq. (II.B.1), g depends on the average power, *i.e.*, $g = g_0/(1 + W/P_{\text{sat}}T_R)$, where g_0 is the unsaturated gain, T_R is the round trip time in the laser cavity, and $W = \int_{-\infty}^{\infty} |U|^2 dt = 2A^2\tau$. In previous work,³² it is often assumed that the laser bandwidth B is determined by the gain bandwidth so that it too is U -dependent. That is not the case for the fiber lasers that we studied. However, for standard figure-8 lasers with the gain medium inside the Sagnac loop, both Γ and K become functions of U , somewhat complicating the analysis. This U -dependence, which is appropriate for gain media with a long response time, as is the case with erbium-doped fiber amplifiers, does not change the equilibrium solution but has a strong impact on the stability of these equilibria. Previous analytical work on the stability³² of these solutions used approximations whose accuracy is hard to gauge. We replaced these approximations with numerical calculations of the eigenvalues of the linear stability equations which is a simple problem numerically.¹⁵ We were then able to calculate stability diagrams that allow us to easily determine the stability of a given laser configuration. We also determined the stability of the cw solution.¹⁶ It is generally assumed that a laser will self-start, *i.e.*, passively modelock starting from noise, when the cw solution is unstable while the modelocked solution is stable. This assumption is supported by simulations.

As part of his Ph.D. thesis, Dr. C.-J. Chen carried out extensive *ab initio* simulations of the fiber ring and figure-8 laser and compared the results to the theory just described.³³ During these studies, it became apparent that the equilibrium solution predicted by Eq. (II.A.1), while qualitatively accurate, has serious quantitative discrepancies from the simulation results, and it is necessary to use a more accurate model of the gain variation with the pulse intensity. Nonetheless, the basic approach that we are using to determine the stability should still prove useful when a more quantitatively accurate equilibrium solution is used.

C. Solid State Devices

Our work on solid state devices has focused on three topics. First, we had a need to benchmark our computer codes in order to determine their accuracy. To do that, we needed to use highly accurate solvers to obtain a baseline solution since analytical solutions do not exist for the cases of interest to us. We developed an algorithm based on Richardson extrapolation³⁴ that proved to have several additional advantages. First, it allowed us to solve the paraxial wave equation that describes propagation in solid state waveguides using explicit rather than implicit solvers. On CRAY computers in which we could take advantage of the increased parallelism of the resulting algorithm, computation times were competitive with less accurate implicit solvers.³⁵ Another advantage is that it was possible to combine an explicit solver with transparent boundary conditions,³⁵ leading to further increases in accuracy and reductions in computation time. A key feature in obtaining efficient computations was the introduction of variable initial steps and subdivisions.³⁶ We note that while Richardson extrapolation has been widely used to solve partial differential equations in other fields,³⁷ its use in photonic modeling is new. The paraxial wave equation that we solved is

$$i\frac{\partial\psi}{\partial z} + \frac{1}{2k_0}\frac{\partial^2\psi}{\partial x^2} + \frac{\omega^2}{2c^2k_0}[n^2(x,z) - n_0^2]\psi = 0, \quad (\text{II.C.1})$$

where ψ is the wave envelope, x and z are the transverse and propagation coordinates, k_0 is the central propagation wavenumber, ω is the central frequency, n is the actual index of refraction, and n_0 is a reference index that is typically chosen to be intermediate between the substrate and guide indices. In all the problems that we examined, it was legitimate to reduce the problems to one transverse dimension by using the effective index approximation. We examined Y-junction and straight waveguide geometries with arbitrary inputs. It was the need to deal with arbitrary inputs and the resulting radiation accurately that led to the need for accurate computational solvers.

The next topic that we examined was electrostatically induced waveguides. While a graduate student at U. C. Santa Barbara, T. C. Huang and his co-workers invented these waveguides.³⁸ In contrast to standard solid state waveguides in which the index difference is fixed by the deposition process that creates the waveguides, the index difference in this case is determined by an external voltage. Not only does that allow the user to directly turn on and off arms of the waveguide, but it allows the user to tune the index difference and hence the effective length by tuning the voltage difference, so that these switches have potential applications to packet-switched networks. Dr. Huang, who was an NRC post-doctoral associate, and his colleagues at the Army Research Laboratory invited us to collaborate in understanding their current experimental results and exploring new device designs. Our simulations were based on the use of Eq. (II.C.1) combined with the effective index method. We studied both a Y-junction design that had already been built and a straight waveguide design that was envisioned. We calculated the crosstalk, loss, and tuning range of the devices.^{17,18,39} We showed that the crosstalk is increased by the loss and that a tuning range of 400 nm is achievable. By contrast, standard LiNbO_3 waveguides typically have tuning ranges of less than 50 nm. We also showed that there must be a

steady source of loss, not previously known, which was later identified as being due to the proton-implementation process that created the waveguides. These results should significantly impact the next generation of these devices.

The final topic that we examined was quasi-phase-matched waveguides. In general, it is not possible to use waveguides for second harmonic generation because when $\omega_2 = 2\omega_1$, i.e., the frequency of the second harmonic is properly matched to the fundamental, then $k_2 \neq 2k_1$, so that the wavenumbers are not properly matched. Lim, *et al.*⁴⁰ showed that it is possible to circumvent these difficulties by changing the nonlinear index with a period that equals $2\pi/\Delta k$, where $\Delta k = k_2 - 2k_1$. Shortly thereafter, Bierlein, *et al.*⁴¹ showed that the unique properties of KTP could be used to create quasi-phase-matched waveguides with nearly perfect domain walls. Large increases in the efficiencies resulted. This led to a series of works, including the recent integration of a quasi-phase-matched waveguide with a Bragg grating and a butt-coupled laser diode.⁷ Since the linear index of the guide is altered periodically, there is a loss that is induced in the quasi-phase-matched waveguides and minimizing these losses is a key device requirement. To calculate these losses, we have developed an innovative approach in which we integrate a series of δ -function inputs over one period of the waveguide, allowing us to determine the impulse response of the guide with a minimum of boundary-interference effects.¹⁹ We have developed an analytical theory for the loss that is in good agreement with the numerical simulations, and we are now engaged in exploring rhomboid and circular shapes for the quasi-phase-matched waveguides that minimize Bragg reflections in collaboration with John Bierlein's research group at the Du Pont Experimental Station.

D. Other Activities

We have three other significant, grant-related activities to report. First, we have carried out studies on $\chi^{(2)}$ cascaded solitons and solitary waves in collaboration with Lluís Torner at the Polytechnic University in Catalonia, Spain and George Stegeman's experimental group at the University of Central Florida. We solved the basic equations that model second harmonic generation with both one and two transverse dimensions. We showed that solitons are robust with one transverse dimension,^{22,23} consistent with the robustness hypothesis,²⁰ and we have shown that stable solitary waves exist with two transverse dimensions, in sharp contrast to Kerr media. Both predictions have been experimentally verified.⁴² We have carried out fundamental studies on the robustness of solitons,²⁰ leading to robustness hypotheses that have been studied in a variety of physical contexts both theoretically and experimentally. Finally, we have greatly improved our graphics capabilities. We have migrated from DISSPLA-based graphics to NCAR-based graphics for pre-processing in the CRAY computers. We have also acquired a high-end ONYX SGI workstation. It presently has an R4400 processor, but we expect to upgrade it to an R8000 processor within the next few months, and the machine should then operate at 350 Mflops. In conjunction with MATLAB, whose recent versions have enormously improved graphics capabilities, we have produced direct computer-generated presentations in which the phase information is represented by false color. These include a mini-course

that we presented to the submarine lightsystems department at AT&T Bell Laboratories and other local laboratories. These tools are very powerful, and we expect to be using them for many of our conference presentations in the future.

E. Publications and Presentations

PH.D. DISSERTATIONS

1. C.-J. Chen, *Theoretical Study of Passively Modelocked Lasers with Fast Saturable Absorbers* (Ph.D. Thesis, August, 1993).
2. V. R. Chinni, *Numerical Study of Integrated Optical Waveguide Devices* (Ph.D. Thesis, August, 1994).

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1. C.J. Chen, P.K.A. Wai, and C.R. Menyuk, "Soliton Fiber Ring Laser," *Optics Lett.* **17**, 417-419 (1992).
2. C.R. Menyuk, "Soliton Robustness in Optical Fibers," *J. Opt. Soc. Am. B* **10**, 1585-1591 (1993).
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5. I.N. Duling, III, C.-J. Chen, P.K.A. Wai, and C.R. Menyuk, "Operation of a Nonlinear Loop Mirror in a Laser Cavity," *IEEE J. Quantum Electron.* **30**, 194-199 (1994).
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7. V.R. Chinni, C.R. Menyuk, and P.K.A. Wai, "Accurate Solution of the Paraxial Wave Equation Using Richardson Extrapolation," *IEEE Photon. Tech. Lett.* **6**, 409-411 (1994).
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13. V.R. Chinni, C.R. Menyuk, and P.K.A. Wai, "Accurate solution of light propagation in optical waveguides using Richardson extrapolation," *J. Math. Comp.* **37**, 279-291 (1994).

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16. M.W. Chbat, C.R. Menyuk, I. Glesk, and P.R. Prucnal, "Interactions of Bound Multiple Solitons in Strongly Birefringent Fibers," *Optics Lett.* **20**, 258-260 (1995).
17. C.-J. Chen, P.K.A. Wai, and C.R. Menyuk, "Self-starting of Passively Mode-locked Lasers With Fast Saturable Absorbers," *Optics Lett.* **20**, 350-352 (1995).
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26. P.K.A. Wai and C.R. Menyuk, "Polarization Mode Dispersion, Decorrelation, and Diffusion in Optical Fibers With Randomly Varying Birefringence," *J. Lightwave Technol.* **14**, 148-157 (1996).

PROCEEDING PUBLICATIONS

1. C.R. Menyuk and P.K.A. Wai, "Soliton Propagation in an Optical Fiber With Randomly Varying Birefringence," in *Proceedings of the Tenth Symposium on Energy Engineering Science*, edited by O.P. Manley (Office of Scientific and Technical Information, Oak Ridge, TN, 1992), pp. 233-240.
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by R. Vichnevetsky, D. Knight, and G. Richter (IMACS, New Brunswick, NJ, 1992), pp. 510-516.

3. C.R. Menyuk and P.K.A. Wai, "Solitons in Optical Fibers With Randomly Varying Birefringence," in *Proceedings of the 1993 International Symposium on Nonlinear Theory and Its Applications*, edited by M. Tanaka and T. Saito (IEICE, Tokyo, Japan, 1993), vol. 3, pp. 917-922
4. C.R. Menyuk, "Effets de biréfringence aléatoire sur la propagation des solitons dans une fibre optique," in *Optique Guidée et Photonique 3*, edited by S. Lacroix (Ecole Polytechnique, Montreal, Canada, 1994), pp. 111-113.
5. C.R. Menyuk and P.K.A. Wai, "Solitons in Optical Fibers With Randomly Varying Birefringence," in *19th ACOFT Proceedings*, edited by M. W. Austin (Telecom Australia, Melbourne, Australia, 1994), pp. 33-36.
6. G.I. Stegeman, R. Schiek, G. Krijnen, W. Torruellas, M. Sundheimer, E. VanStryland, C. Menyuk, L. Torner and G. Assanto, "Cascading: Modelling a New Route to Large Optical Nonlinearities and All-Optical Devices," in *Guided-Wave Optoelectronics: Device Characterization, Analysis, and Design, Proceedings of the 4th WRI International Conference on Guided Wave Optoelectronics*, edited by T. Tamir, H. Bertoni and G. Griffel (Plenum Press, New York, 1995), 371-379.

CONFERENCE PRESENTATIONS

* indicates invited presentation

1. V.R. Chinni, C.R. Menyuk, and Y.J. Chen, "Propagation Characteristics of GaAs/AlGaAs QW Ridge Waveguides," S.P.I.E. Conference on Emerging Optoelectronic Technologies, Bangalore, India (Dec. 16-21, 1991).
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