3.14 The material dispersion in an optical fiber defined by $|d^2n_1/d\lambda^2|$ is $4.0 \times 10^{-2}\ \mu m^{-2}$. Estimate the pulse broadening per kilometre due to material dispersion within the fiber when it is illuminated with an LED source with a peak wavelength of 0.9 μm and an rms spectral width of 45 nm.

3.15 Describe the mechanism of intermodal dispersion in a multimode step index fiber.

Show that the total broadening of a light pulse δT_s due to intermodal dispersion in a multimode step index fiber may be given by:

$$\delta T_s \simeq \frac{L(NA)^2}{2n_1c}$$

where L is the fiber length, NA is the numerical aperture of the fiber, n_1 is the core refractive index and c is the velocity of light in a vacuum.

A multimode step index fiber has a numerical aperture of 0.2 and a core refractive index of 1.47. Estimate the bandwidth–length product for the fiber assuming only intermodal dispersion and a return to zero code when:

(a) there is no mode coupling between the guided modes;

(b) mode coupling between the guided modes gives a characteristic length equivalent to 0.6 of the actual fiber length.

3.16 Using the relation for δT_s given in Problem 3.15, derive an expression for the rms pulse broadening due to intermodal dispersion in a multimode step index fiber. Compare this expression with a similar expression which may be obtained for an optimum near parabolic profile graded index fiber.

Estimate the bandwidth–length product for the step index fiber specified in Problem 3.15 considering the rms pulse broadening due to intermodal dispersion within the fiber and comment on the result. Indicate the possible improvement in the bandwidth–length product when an optimum near parabolic profile graded index fiber with the same relative refractive index difference and core axis refractive index is used. In both cases assume only intermodal dispersion within the fiber and the use of a return to zero code.

3.17 An 11 km optical fiber link consisting of optimum near parabolic profile graded index fiber exhibits rms intermodal pulse broadening of 346 ps over its length. If the fiber has a relative refractive index difference of 1.5%, estimate the core axis refractive index. Hence determine the numerical aperture for the fiber.

3.18 A multimode, optimum near parabolic profile graded index fiber has a material dispersion parameter of 30 ps nm^{-1} km^{-1} when used with a good LED source of rms spectral width 25 nm. The fiber has a numerical aperture of 0.4 and a core axis refractive index of 1.48. Estimate the total rms pulse broadening per kilometre within the fiber assuming waveguide dispersion to be negligible. Hence, estimate the bandwidth–length product for the fiber.

3.19 A multimode step index fiber has a relative refractive index difference of 1% and a core refractive index of 1.46. The maximum optical bandwidth that may be obtained with a particular source on a 4.5 km link is 3.1 MHz.

(a) Determine the rms pulse broadening per kilometre resulting from intramodal dispersion mechanisms.

(b) Assuming waveguide dispersion may be ignored, estimate the rms spectral width of the source used, if the material dispersion parameter for the fiber at the operating wavelength is 90 ps nm^{-1} km^{-1}

3.20 Describe the phenomenon of modal noise in optical fibers and suggest how it may be avoided.

3.21 Discuss dispersion mechanisms with regard to single-mode fibers indicating the dominating effects. Hence, describe how intramodal dispersion may be minimized within the single-mode region.

3.22 An approximation for the normalized propagation constant in a single-mode step index fiber shown in Example 2.9 is:

$$b(V) \simeq \left(1.1428 - \frac{0.9960}{V}\right)^2$$

Obtain a corresponding approximation for the waveguide parameter $V\,d^2(Vb)/dV^2$ and hence write down an expression for the waveguide dispersion in the fiber.

Estimate the waveguide dispersion in a single-mode step index fiber at a wavelength 1.34 μm when the fiber core radius and refractive index are 4.4 μm and 1.48 respectively.

3.23 A single-mode step index fiber exhibits material dispersion of 7 ps nm^{-1} km^{-1} at an operating wavelength of 1.55 μm. Using the approximation obtained in Problem 3.22, estimate the fiber core diameter which will enable the waveguide dispersion to cancel the material dispersion so that zero intramodal dispersion is obtained at this wavelength. The refractive index of the fiber core is 1.45.

3.24 A single-mode step index fiber has a zero-dispersion wavelength of 1.29 μm and exhibits total first order dispersion of 3.5 ps nm^{-1} km^{-1} at a wavelength of 1.32 μm. Determine the total first order dispersion in the fiber at a wavelength of 1.54 μm.

3.25 Describe the techniques employed and the fiber structures utilized to provide:

(a) dispersion shifted single-mode fibers;
(b) dispersion flattened single-mode fibers.

3.26 Explain what is meant by:

(a) modal birefringence;
(b) the beat length;

in single-mode fibers.

The difference between the propagation constants for the two orthogonal modes in a single-mode fiber is 250. It is illuminated with light of peak wavelength 1.55 μm from an injection laser source with a spectral linewidth of 0.8 nm. Estimate the coherence length within the fiber.

3.27 The difference in the effective refractive indices $(n_x - n_y)$ for the two orthogonally polarized modes in conventional single-mode fibers are in the range $9.3 \times 10^{-7} < n_x - n_y < 1.1 \times 10^{-5}$ Determine the corresponding range for the beat lengths of the fibers when they are operating at a transmission wavelength of 1.3 μm. Hence obtain the range of the modal birefringence for the fibers.

3.28 A single-mode fiber maintains birefringent coherence over a length of 100 km when it is illuminated with an injection laser source with a spectral linewidth of 1.5 nm and a peak wavelength of 1.32 μm. Estimate the beat length within the fiber and comment on the result.

3.29 Provide a definition for polarization mode dispersion in single-mode optical fibers.

The maximum bit rate that can be achieved over a 6 km length of highly birefringent single-mode fiber is 400 kbit s^{-1}. Assuming polarization mode dispersion to be the dominant dispersive mechanism, calculate its value within this fiber.

3.30 Describe, with the aid of sketches, the techniques that can be employed to produce both high and low birefringence PM fibers.

A two polarization mode PM fiber has a mode coupling parameter of 2.3×10^{-5} m^{-1} when operating at a wavelength of 1.55 μm. Estimate the polarization crosstalk for the fiber at this wavelength.

3.31 Explain what is meant by self phase modulation.

Identify and discuss a major application area for this nonlinear phenomenon.

Answers to numerical problems

3.1 57.5 km
3.2 10.0 μW
3.3 703 μW
3.5 1.57 dB km^{-1}, 0.14 dB km^{-1}
3.6 1.49
3.7 1.50 μm, 0.30 dB km^{-1}
3.8 2.4 W
3.9 0.86 μm
3.10 0.47%
3.11 (a) 13.2 MHz km; (b) 800 ps
3.12 (a) 10 ns; (b) 4 ns
3.13 1.2 ns
3.14 5.4 ns km^{-1}
3.15 (a) 11.0 MHz km; (b) 14.2 MHz km
3.16 15.3 MHz km; improvement to 10.9 GHz km
3.17 1.45, 0.25
3.18 774 ps km^{-1}, 258 MHz km
3.19 (a) 2.82 ns km^{-1}; (b) 31 nm
3.22 -3.92 ps nm^{-1} km^{-1}
3.23 7.2 μm
3.24 23.6 ps nm^{-1} km^{-1}
3.26 48.6 m
3.27 12 cm $< L_B <$ 1.4 m; $9.3 \times 10^{-7} < B_F < 1.1 \times 10^{-5}$
3.28 113.6 m
3.29 682 ps km^{-1}
3.30 -16.4 dB km^{-1}

References

[1] F. P. Kapron, D. B. Keck and R. D. Maurer, 'Radiation losses in optical waveguides', *Appl. Phys. Lett.*, **10**, pp. 423–425, 1970.

[2] S. R. Nagel, 'Optical fiber – the expanding medium', *IEEE Commun. Mag.*, **25**(4), pp. 33–43, 1987.

[3] T. Miya, Y. Teramuna, Y. Hosaka and T. Miyashita, 'Ultimate low-loss single-mode fibre at 1.55 μm', *Electron. Lett.*, **15**(4), pp. 106–108, 1979.

[4] P. C. Schultz. 'Preparation of very low loss optical waveguides', *J. Am. Ceram. Soc.*, **52**(4), pp. 383–385, 1973.

[5] H. Osanai, T. Shioda, T. Morivama, S. Araki, M. Horiguchi, T. Izawa and H. Takata, 'Effect of dopants on transmission loss of low OH-content optical fibres', *Electron. Lett.*, **12**(21), pp. 549–550, 1976.

[6] D. B. Keck, R. D. Maurer and P. C. Schultz, 'On the ultimate lower limit of attenuation in glass optical waveguides', *Appl. Phys. Lett.*, **22**(7), pp. 307–309, 1973.

[7] A. R. Tynes, A. D. Pearson and D. L. Bisbee, 'Loss mechanisms and measurements in clad glass fibers and bulk glass', *J. Opt. Soc. Am.*, **61**, pp. 143–153, 1971.

[8] K. J. Beales and C. R. Day, 'A review of glass fibres for optical communications' *Phys. Chem. Glasses*, **21**(1), pp. 5–21, 1980.

[9] R. Olshansky, 'Propagation in glass optical waveguides', *Rev. Mod. Phys.*, **51**(2), pp. 341–367, 1979.

[10] R. M. Gagliardi and S. Karp, *Optical Communications*, John Wiley, 1976.

[11] J. Schroeder, R. Mohr, P. B. Macedo and C. J. Montrose, 'Rayleigh and Brillouin scattering in K_2O–SiO_2 glasses', *J. Am. Ceram. Soc.*, **56**, pp. 510–514, 1973.

[12] R. D. Maurer, 'Glass fibers for optical communications', *Proc. IEEE*, **61**, pp. 452–462, 1973.

[13] D. A. Pinnow, T. C. Rich, F. W. Ostermayer Jr and M. DiDomenico Jr, 'Fundamental optical attenuation limits in the liquid and glassy state with application to fiber optical waveguide materials', *App. Phys. Lett.*, **22**, pp. 527–529, 1973.

[14] E. A. J. Marcatili, 'Objectives of early fibers: evolution of fiber types', in S. E. Miller and A. G. Chynoweth (Eds.), *Optical Fiber Telecommunications*, pp. 1–35, Academic Press, 1979.

[15] D. Gloge, 'Propagation effects in optical fibers', *IEEE Trans. Microwave Theory Tech.*, **MTT-23**, pp. 106–120, 1975.

[16] R. H. Stolen, 'Nonlinearity in fiber transmission', *Proc. IEEE*, **68**(10), pp. 1232–1236, (1980).

[17] R. H. Stolen, 'Nonlinear properties of optical fibers', in S. E. Miller and A. G. Chynoweth (Eds.), *Optical Fiber Telecommunications*, pp. 125–150, Academic Press, 1979.

[18] Y. Ohmori, Y. Sasaki and T. Edahiro, 'Fiber-length dependence of critical power for stimulated Raman scattering', *Electron. Lett.*, **17**(17), pp. 593–594, 1981.

[19] M. M. Ramsay and G. A. Hockham, 'Propagation in optical fibre waveguides', in C. P. Sandbank (Ed.), *Optical Fibre Communication Systems*, pp. 25–41, John Wiley, 1980.

[20] H. F. Wolf, 'Optical waveguides', in H. F. Wolf (Ed.), *Handbook of Fiber Optics: Theory and Applications*, pp. 43–152, Granada, 1979.

[21] W. A. Gambling, H. Matsumura and C. M. Ragdale, 'Curvature and microbending losses in single mode optical fibres', *Opt. Quantum Electron.*, **11**, pp. 43–59, 1979.

[22] T. Li, 'Structures, parameters and transmission properties of optical fibers', *Proc. IEEE*, **68**(10), pp. 1175–1180, 1980.

[23] J. A. Savage, 'Materials for infrared fibre optics', *Materials Science Reports*, **2**, pp. 99–138, 1987.

[24] W. H. Dumbaugh, 'Oxide glasses with superior infrared transmission', *Proc. SPIE Int. Soc. Opt. Eng (USA)*, **505**, pp. 97–101, 1984.

[25] M. Saito, M. Takizawa and M. Miyagi, 'Optical and mechanical properties of infrared fibers', *J. of Lightwave Technol.*, **6**(2), pp. 233–239, 1988.

[26] S. R. Nagel, 'Fiber materials and fabrication methods', in *Optical Fiber Telecommunications II*, S. E. Miller and I. P. Kaminow (Eds.), pp. 121–215, Academic Press Inc., 1988.

[27] S. Sakaguchi and S. Takahashi, 'Low-loss fluoride optical fibers for midinfrared optical communication', *J. of Lightwave Technol.*, **LT-5**(9), pp. 1219–1228, 1987.

[28] M. Nishimura, 'The two modes of a "single-mode" fiber', *Photonics Spectra*, **20**(6), pp. 109–116, June 1986.

[29] Y. Ohishi and S. Takahashi, 'Low-dispersion fluoride glass single-mode fibres operating in two spectral ranges', *Electron. Lett.*, **24**(4), pp. 220–221, 1988.

[30] A. Bornstein and N. Croitoru, 'Experimental evaluation of a hollow glass fiber', *Appl. Opt.*, **25**(3), pp. 355–358, 1986.

[31] I. P. Kaminow, D. Marcuse and H. M. Presby, 'Multimode fiber bandwidth: theory and practice', *Proc. IEEE*, **68**(10), pp. 1209–1213, 1980.
[32] M. J. Adams, D. N. Payne, F. M. Sladen and A. H. Hartog, 'Optimum operating wavelength for chromatic equalisation in multimode optical fibres', *Electron. Lett.*, **14**(3), pp. 64–66, 1978.
[33] W. A. Gambling, A. H. Hartog and C. M. Ragdale, 'Optical fibre transmission lines', *Radio Electron. Eng. J. IERE*, **51**(7/8), pp. 313–325, 1981.
[34] D. N. Payne and W. A. Gambling, 'Zero material dispersion in optical fibres', *Electron. Lett.*, **11**(8), pp. 176–178, 1975.
[35] F. P. Kapron and D. B. Keck, 'Pulse transmission through a dielectric optical waveguide', *Appl. Opt.*, **10**(7), pp. 1519–1523, 1971.
[36] M. DiDomenico Jr, 'Material dispersion in optical fiber waveguides', *Appl. Opt.*, **11**, pp. 652–654, 1972.
[37] F. G. Stremler, *Introduction in Communication Systems*, 2nd edn, Addison-Wesley, 1982.
[38] D. Botez and G. J. Herkskowitz, 'Components for optical communication systems: a review', *Proc. IEEE*, **68**(6), pp. 689–730, 1980.
[39] A. Ghatak and K. Thyagarajan, 'Graded index optical waveguides: a review', in E. Wolf (Ed.), *Progress in Optics*, pp. 1–109, North-Holland Publishing, 1980.
[40] D. Gloge and E. A. Marcatili, 'Multimode theory of graded-core fibers', *Bell Syst. Tech. J.*, **52**, pp. 1563–1578, 1973.
[41] J. E. Midwinter, *Optical Fibers for Transmission*, John Wiley, 1979.
[42] R. Olshansky and D. B. Keck, 'Pulse broadening in graded-index optical fibers', *Appl. Opt.*, **15**(12), pp. 483–491, 1976.
[43] R. E. Epworth, 'The phenomenon of modal noise in analogue and digital optical fibre systems', in *Proceedings of the 4th European Conference on Optical Communication*, Italy, pp. 492–501, 1978.
[44] A. R. Godwin, A. W. Davis, P. A. Kirkby, R. E. Epworth and R. G. Plumb, 'Narrow stripe semiconductor laser for improved performance of optical communication systems', *Proceedings of the 5th European Conference on Optical Communications*, The Netherlands, paper 4–3, 1979.
[45] K. Sato and K. Asatani, 'Analogue baseband TV transmission experiments using semiconductor laser diodes', *Electron. Lett.*, **15**(24), pp. 794–795, 1979.
[46] B. Culshaw, 'Minimisation of modal noise in optical-fibre connectors', *Electron. Lett.*, **15**(17), pp. 529–531, 1979.
[47] N. K. Cheung, A. Tomita and P. F. Glodis, 'Observation of modal noise in single-mode fiber transmission systems', *Electron. Lett.*, **21**, pp. 5–7, 1985.
[48] F. M. Sears, I. A. White, R. B. Kummer and F. T. Stone, 'Probability of modal noise in single-mode lightguide systems', *J. of Lightwave Technol.*, **LT-4**, pp. 652–655, 1986.
[49] D. Gloge, 'Dispersion in weakly guiding fibers', *Appl. Opt.*, **10**(11), pp. 2442–2445, 1971.
[50] W. A. Gambling, H. Matsumura and C. M. Ragdale, 'Mode dispersion, material dispersion and profile dispersion in graded index single-mode fibers', *IEEJ. Microwaves, Optics and Acoustics (GB)*, **3**(6), pp. 239–246, 1979.
[51] E. G. Neumann, *Single-Mode Fibers: Fundamentals*, Springer Verlag, 1988.
[52] J. W. Fleming, 'Material dispersion in lightguide glasses', *Electron. Lett.*, **14**(11), pp. 326–328, 1978.

[53] J. I. Yamada, M. Saruwatari, K. Asatani, H. Tsuchiya, A. Kawana, K. Sugiyama and T. Kimura, 'High speed optical pulse transmission at 1.29 μm wavelength using low-loss single-mode fibers', *IEEE J. Quantum Electron.*, **QE-14**, pp. 791–800, 1978.
[54] CCITT, COM.XV/TD 46-E, 'Revised version of Recommendation G.652 Characteristics of a single-mode fiber cable', May 1984.
[55] F. P. Kapron, 'Chromatic dispersion format for single-mode and multimode fibers', *Conf. Dig. Opt. Fiber Commun., OFC'87* (USA), paper TUQ2, January 1987.
[56] F. P. Kapron, 'Dispersion-slope parameter for monomode fiber bandwidth', *Conf. Opt. Fiber Commun. OFC'84* (USA), pp. 90–92, January 1984.
[57] F. P. Kapron, 'Maximum information capacity of fibre-optic waveguides', *Electron. Lett.*, **13**(4), pp. 96–97, 1977.
[58] P. Kaiser and D. B. Keck, 'Fiber types and their status', in *Optical Fiber Telecommunications* II, S. E. Miller and I. P. Kaminow (Eds.), pp. 29–54, Academic Press Inc., 1988.
[59] V. A. Bhagavatula, J. C. Lapp, A. J. Morrow and J. E. Ritter, 'Segmented-core fiber for long-haul and local-area-network applications', *J. of Lightwave Technol.*, **6**(10), pp. 1466–1469, 1988.
[60] L. G. Cohen, 'Comparison of single mode fiber dispersion measurement techniques', *J. Lightwave Technol.*, **LT-3**, pp. 958–966, 1985.
[61] B. J. Ainslie and C. R. Day, 'A review of single-mode fibers with modified dispersion characteristics', *J. of Lightwave Technol.*, **LT-4**(8), pp. 967–979, 1986.
[62] B. J. Ainslie, K. J. Beales, C. R. Day and J. D. Rush, 'Interplay of design parameters and fabrication conditions on the performance of monomode fibers made by MCVD', *IEEE. J. Quantum Electron.*, **QE-17**, pp. 854–857, 1981.
[63] M. A. Saifi, 'Triangular index monomode fibres', *Proc. SPIE Int. Soc. Opt. Eng.* (USA), **374**, pp. 13–15, 1983.
[64] W. A. Gambling, H. Matsumura and C. M. Ragdale, 'Zero total dispersion in graded-index single mode fibres', *Electron. Lett.*, **15**, pp. 474–476, 1979.
[65] B. J. Ainslie, K. J. Beales, D. M. Cooper and C. R. Day, 'Monomode optical fibres with graded-index cores for low dispersion at 1.55 μm', *Br. Telecom Technol. J.*, **2**(2), pp. 25–34, 1984.
[66] H.-T. Shang, T. A. Lenahan, P. F. Glodis and D. Kalish, 'Design and fabrication of dispersion-shifted depressed-clad triangular-profile (DDT) single-mode fibre', *Electron. Lett.*, **21**, pp. 484–486, 1982.
[67] M. Miyamoto, T. Abiru, T. Ohashi, R. Yamauchi and O. Fukuda, 'Gaussian profile dispersion-shifted fibers made by VAD method', in *Proc. IOOC-ECOC'85* (Venice, Italy), pp. 193–196, 1985.
[68] D. M. Cooper, S. P. Craig, C. R. Day and B. J. Ainslie, 'Multiple index structures for dispersion shifted single mode fibers using multiple index structures', *Br. Telecom Technol. J.*, **3**, pp. 52–58, 1985.
[69] V. A. Bhagavatula and P. E. Blaszyk, 'Single mode fiber with segmented core', *Conf. Dig. Opt. Fiber Commun. OFC'83*, New Orleans, USA, Paper MF5, 1983.
[70] A. R. Hunwicks, P. A. Rosher, L. Bickers and D. Stanley, 'Installation of dispersion-shifted fibre in the British Telecom trunk network', *Electron. Lett.*, **24**(9), pp. 536–537, 1988.
[71] V. Bhagavatula, M. S. Spotz, W. F. Love and D. B. Keck, 'Segmented core single mode fibre with low loss and low dispersion', *Electron. Lett.*, **19**(9), pp. 317–318, 1983.

[72] N. Kuwaki, M. Ohashi, C. Tanaka, N. Uesugi, S. Seikai and Y. Negishi, 'Characteristics of dispersion-shifted dual shape core single-mode fiber', *J. Lightwave Technol.*, **LT-5**(6), pp. 792–797, 1987.

[73] K. Nishide, D. Tanaka, M. Miyamoto, R. Yamauchi and K. Inada, 'Long-length and high-strength dual-shaped core dispersion-shifted fibers made by a fully synthesized VAD method', in *Conf. Dig. Opt. Fiber Commun. OFC'88*, New Orleans, USA, Paper WI2, 1988.

[74] T. Miya, K. Okamoto, Y. Ohmori and Y. Sasaki, 'Fabrication of low dispersion single mode fibers over a wide spectral range', *IEEE J. Quantum Electron.*, **QE-17**, pp. 858–861, 1981.

[75] J. J. Bernard, C. Brehm, P. H. Dupont, G. M. Gabriagues, C. Le Sergeant, M. Liegois, P. L. Francois, M. Monerie and P. Sansonetti, 'Investigation of the properties of depressed inner cladding single-mode fibres', in *Proc. 8th Eur. Conf. Opt. Commun.* (Cannes, France), pp. 133–138, 1982.

[76] L. G. Cohen, W. L. Mammel and S. J. Jang, 'Low-loss quadruple-clad single-mode lightguides with dispersion below 2 ps/km nm over the 1.28 μm–1.65 μm wavelength range', *Electron. Lett.*, **18**, pp. 1023–1024, 1982.

[77] S. J. Jang, J. Sanchez, K. D. Pohl and L. D. L'Esperançe, 'Graded-index single-mode fibers with multiple claddings', in *Proc. IOOC'83* (Tokyo, Japan), pp. 396–397, 1983.

[78] V. A. Bhagavatula, 'Dispersion-modified fibers', *Conf. Dig. Opt. Fiber Commun. OFC'88*, New Orleans, USA, Paper WI1, 1988.

[79] P. K. Backmann, D. Leers, H. Wehr, D. U. Wiechert, J. A. Steenwijk, D. L. A. Tjaden and E. R. Wehrhatim, 'Dispersion-flattened single-mode fibers prepared with PCVD: performance, limitations, design optimization', *J. Lightwave Technol.*, **LT-4**, pp. 858–863, 1986.

[80] M. Monerie, D. Moutonnet and L. Jeunhomme, 'Polarisation studies in long length single mode fibres', in *Proceedings of the 6th European Conference on Optical Communication*, UK, pp. 107–111, 1980.

[81] I. P. Kaminow, 'Polarization in fibers', *Laser Focus*, **16**(6), pp. 80–84, 1980.

[82] I. P. Kaminow, 'Polarization in optical fibers', *IEEE J. Quantum Electron.*, **QE-17**(1), pp. 15–22, 1981.

[83] S. C. Rashleigh and R. Ulrich, 'Polarization mode dispersion in single-mode fibers', *Opt. Lett.*, **3**, pp. 60–62, 1978.

[84] V. Ramaswamy, R. D. Standley, D. Sze and W. G. French, 'Polarisation effects in short length, single mode fibres', *Bell Syst. Tech. J.*, **57**, pp. 635–651, 1978.

[85] A. Papp and H. Harms, 'Polarization optics of index-gradient optical waveguide fibers', *Appl. Opt.*, **14**, pp. 2406–2411, 1975.

[86] K. Mochizuki, Y. Namihira and H. Wakabayashi, 'Polarization mode dispersion measurements in long single mode fibers', *Electron. Lett.*, **17**, pp. 153–154, 1981.

[87] Y. Sasaki, T. Hosaka and J. Noda, 'Fabrication of polarization-maintaining optical fibers with stress-induced birefringence', *Rev. Electr. Commun. Lab.*, NTT, Japan, **32**, pp. 452–460, 1984.

[88] D. N. Payne, A. J. Barlow and J. J. Ramskov Hansen, 'Development of low-and-high-birefringence optical fibers', *IEEE J. of Quantum Electron.*, **QE-18**(4) pp. 477–487, 1982.

[89] K. Kitayama, Y. Kato, S. Seikai and N. Uchida, 'Structural optimization for two-mode fiber: theory and experiment', *IEEE J. Quantum Electron*, **QE-17**, pp. 1057–1063, 1988.

[90] K. Suzuki, N. Shibata and Y. Ishida, 'Polarization-mode dispersion as a bandwidth-limiting factor in a long-haul single-mode optical-transmission system', *Electron. Lett.*, **19**, pp. 689–691, 1983.

[91] I. P. Kaminow, 'Polarization-maintaining fibers', *Appl. Scient. Research*, **41**, pp. 257–270, 1984.

[92] F. P. Kapron and P. D. Lazay, 'Monomode fiber measurement techniques and standards', *SPIE, Int. Soc. Opt. Eng.*, **425**, pp. 40–48, 1983.

[93] S. Heckmann, 'Modal noise in single-mode fibers', *Opt. Lett.*, **6**, pp. 201–203, 1981.

[94] R. H. Stolen and R. P. De Paula, 'Single-mode fiber components', *Proc. IEEE*, **75**(11), pp. 1498–1511, 1987.

[95] J. Noda, K. Okamoto and Y. Sasaki, 'Polarization-maintaining fibers and their applications', *J. of Lightwave Technol.*, **LT-4**(8), pp. 1071–1089, 1986.

[96] W. Eickhoff and E. Brinkmeyer, Scattering loss vs. polarization holding ability of single-mode fibers', *Appl. Opt.*, **23**, pp. 1131–1132, 1984.

[97] I. P. Kaminow and V. Ramaswamy, 'Single-polarization optical fibers: Slab model', *Appl. Phys. Lett.*, **34**, pp. 268–70, 1979.

[98] R. D. Birch, D. N. Payne and M. P. Varnham, 'Fabrication of polarization-maintaining fibers using gas-phase etching', *Electron. Lett.*, **18**, pp. 1036–1038, 1982.

[99] T. Hosaka, Y. Sasaki, J. Noda and M. Horiguchi, 'Low-loss and low-crosstalk polarization-maintaining optical fibers', *Electron. Lett.*, **21**, pp. 920–921, 1985.

[100] R. H. Stolen, W. Pleibel and J. R. Simpson, 'High-birefringence optical fibers by preform deformation', *J. Lightwave Technol.*, **LT-2**, pp. 639–641, 1985.

[101] H. Schneider, H. Harms, A. Rapp and H. Aulich, 'Low birefringence single-mode fibers: Preparation and polarization characteristics', *Appl. Opt.*, **17**(19), pp. 3035–3037, 1978.

[102] S. R. Norman, D. N. Payne, M. J. Adams and A. M. Smith, 'Fabrication of single-mode fibers exhibiting extremely low polarization birefringence', *Electron. Lett.*, **15**(11), pp. 309–311, 1979.

[103] D. N. Payne, A. J. Barlow and J. J. Ramskov Hansen, 'Development of low and high birefringent optical fibers', *IEEE J. Quantum Electron*, **QE-18**(4), pp. 477–487, 1982.

[104] W. A. Gambling and S. B. Poole, 'Optical fibers for sensors', in J. P. Dakin and B. Culshaw (Eds.), *Optical Fiber Sensors: Principles and components*, Artech House, pp. 249–276, 1988.

[105] R. D. Birch, 'Fabrication and characterisation of circularly-birefringent helical fibres', *Electron Lett.*, **23**, pp. 50–52, 1987.

[106] T. Hosaka, Y. Sasaki and K. Okamoto, '3-km long single-polarization single-mode fiber', *Electron. Lett.*, **21**(22), pp. 1023–1024, 1985.

[107] H. Kajioka, Y. Takuma, K. Yamada and T. Tokunaga, 'Low-loss polarization-maintaining single-mode fibers for 1.55 μm operation', in *Tech. Dig. Opt. Fiber. Commun. Conf. OFC'88* (New Orleans, USA), paper WA5, 1988.

[108] K. Tajima and Y. Sasaki, 'Transmission loss of a 125 μm diameter PANDA fiber with circular stress-applying parts', *J. Lightwave Technol.*, **7**(4), pp. 674–679, 1989.

[109] H. Winful, 'Nonlinear optical phenomena in single-mode fibers', in E. E. Basch (Ed.), *Optical-Fiber Transmission*, pp. 179–240, Howard W Sams & Co., 1987.

[110] L. B. Jeunhomme, *Single-Mode Fiber Optics*, Marcel Dekker Inc., 1983.

[111] W. J. Tomlinson and R. H. Stolen, 'Nonlinear phenomena in optical fibers', *IEEE Commun. Mag.*, **26**(4), pp. 36–44, 1988.