Dispersion flattening in a w-fiber

Lundin, Richard

1993

LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

CODEN:LUTEDX/(TEAT-7024)/1-7/(1993)

Dispersion flattening in a w-fiber

Richard Lundin

Department of Electroscience
Electromagnetic Theory
Lund Institute of Technology
Sweden

Richard Lundin

Department of Electromagnetic Theory
Lund Institute of Technology
P.O. Box 118
SE-221 00 Lund
Sweden

Editor: Gerhard Kristensson

Abstract

A method for dispersion-flattening in double-clad single-mode optical fibers is presented. The chromatic dispersion over the wavelength range [1.25 μm, 1.60 μm] is minimized for a w-fiber and also for a triangular-index fiber with a depressed inner cladding. The constraint that the first higher order mode should appear exactly at 1.25 μm is imposed. The full vector solution of Maxwell's equations is used. Applying an approximate refractive-index model, it is found that the w-fiber is capable of yielding a rms-dispersion less than 1 ps/(km nm). A doping level of two per cent in the core is necessary to achieve this. How to interpret this numerical result is not clear, since the approximate refractive-index model used is, in this context, crude.

1 Introduction

In order to minimize pulse-broadening in an optical fiber, the chromatic dispersion should be low over the wavelength range used. A fiber in which the chromatic dispersion is low over a broad wavelength range is called a dispersion flattened fiber [1]. This paper is a continuation of the paper [2] in which the rms-value of the chromatic dispersion over the wavelength range [1.25 μm, 1.60 μm] is calculated and minimized for fibers with step-index profiles, triangular-index profiles and α-power profiles. Of these profiles, the step-index profile yields the lowest rms-dispersion, 4.8 ps/(km nm), and this minimum is obtained when the relative refractive-index increase in the core is equal to a factor 1.01.

In this paper the analysis is extended to w-profiles and to triangular-index profiles with a depressed inner cladding.

1.1 An approximate refractive-index model

The actual refractive-index profile $n(r, \lambda_0)$ of an optical fiber is a function of the radial coordinate r and of the vacuum wavelength λ_0. The actual refractive-index profile $n(r, \lambda_0)$ can be written

$$n(r, \lambda_0) = N(r, \lambda_0)\, n_s(\lambda_0) \tag{1.1}$$

where $n_s(\lambda_0)$ is the refractive-index of pure silica and $N(r, \lambda_0)$ is "the normalized refractive-index" or "the relative refractive-index increase".

The following approximation will be made. The normalized refractive-index N is assumed to be a function of the radial coordinate only, i.e.

$$n(r, \lambda_0) = N(r)\, n_s(\lambda_0) \tag{1.2}$$

A Sellmeier formula for the refractive-index of pure "quenched" silica glass given by Fleming [3, 4] is used to model $n_s(\lambda_0)$ where n_s is the refractive-index of pure, i.e. undoped, silica glass and λ_0 is the vacuum wavelength.

1.2 The rms-value f of the chromatic dispersion

The chromatic dispersion in a single-mode fiber is given by

$$C = -\frac{\lambda_0}{c}\frac{d^2 n_e}{d\lambda_0^2} \tag{1.3}$$

where c is the speed of light in a vacuum, n_e is the effective refractive-index of the fundamental mode, and λ_0 is the vacuum wavelength.

The rms-value, or the function f, to be minimized is

$$f = \left(\frac{1}{\lambda_2 - \lambda_1} \int_{\lambda_1}^{\lambda_2} C^2(\lambda_0)\, d\lambda_0 \right)^{1/2} \tag{1.4}$$

A computer program calculates the effective refractive-index for a number of equidistant vacuum wavelengths. This is done by solving the characteristic equation by a root-searching method. The effective refractive-index as a function of the vacuum wavelength is represented by Lagrange interpolation polynomials [2, 5]. The rms-value f is then calculated analytically using (1.3) and (1.4).

The computer program applies the power-series expansion method developed in Ref. [6]. This method yields the full vector solution of Maxwell's equations.

2 Minimization

2.1 w-profiles

A normalized w-profile is given by

$$N(r) = \begin{cases} N_1 & 0 \le r < b \\ N_2 & b \le r < a \\ 1 & r \ge a \end{cases} \tag{2.1}$$

where $N_1 > 1$ and $N_2 \le 1$. The constraint that the first higher order mode should appear exactly at 1.25 μm is imposed. Thus, there are four variables, namely (N_1, N_2, b, a), and one constraint.

Assume that N_1 and N_2 are given some certain fixed values. The values $N_1 = 1.02$ and $N_2 = 0.99$ will prove to be interesting. If $b = a$ then the w-profile has degenerated into a step-index profile. The core radius a of this step-index fiber is easily calculated [2] using the exact cut-off condition $V = j_{01} = 2.405$ where V is the normalized frequency. The value $N_1 = 1.02$ yields $b = a = 1.64$ μm.

Direct numerical calculation yields that if the outer radius a is increased then the inner radius b must also be increased in order to keep the cut-off wavelength at 1.25 μm. Hence, the constraint $\lambda_c = 1.25$ μm corresponds to a curved line in the a-b-plane. The rms-value f of the chromatic dispersion along this line is given in Fig. **??**. The point of minimum dispersion is easily located. This procedure is

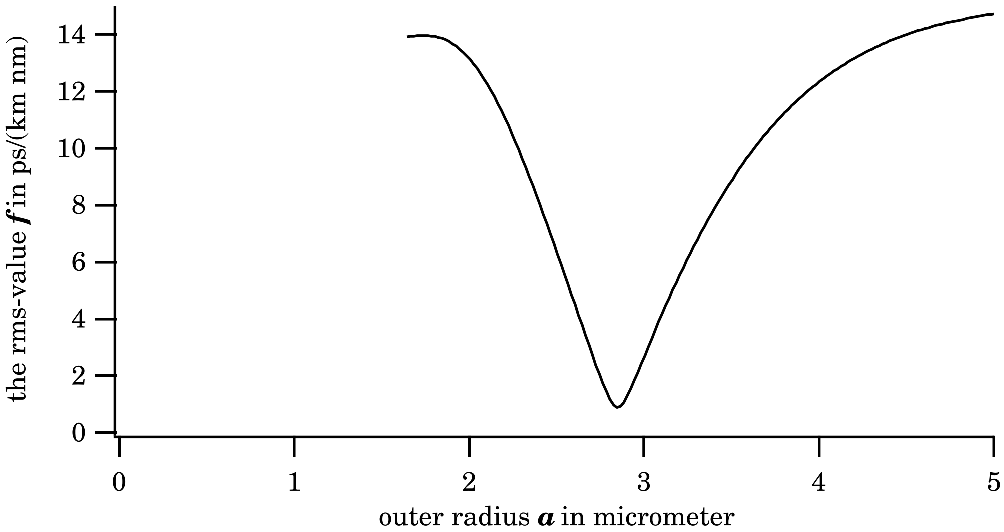

Figure 1: The rms-value f of the chromatic dispersion over the vacuum wavelength range [1.25 μm, 1.60 μm] as a function of the outer radius a in a w-fiber. The cut-off vacuum wavelength is 1.25 μm. The relative refractive-index increase in the core and in the inner cladding is 1.02 and 0.99 respectively.

repeated for different combinations of N_1 and N_2 and the result is given in Table 1. The first column of this table, i.e. $N_2 = 1$, corresponds to step-index profiles.

According to Table 1, the global minimum is 0.9 ps/(km nm) and the corresponding "optimal" w-fiber is $(N_1, N_2, b, a) = (1.02, 0.99, 1.91\ \mu\text{m}, 2.85\ \mu\text{m})$, see Fig. **??**. It should be observed that the global minimum is flat, i.e., there is a "valley" in Table 1 giving roughly the same rms-dispersion. Another observation is that the dependence of N_2 in Table 1 is weak if N_1 is less than 1.01. On the other hand, the dependence of N_2 is strong if N_1 is greater than 1.01 and N_2 is close to unity.

		N_2				
		1.000	0.995	0.990	0.985	0.980
N_1	1.002	12.	12.	12.	12.	12.
	1.005	8.6	8.6	8.5	8.5	8.5
	1.010	4.8	4.3	4.2	4.1	4.1
	1.015	7.9	2.3	1.8	1.6	1.5
	1.020	14.	1.3	0.9	1.0	1.2
	1.025	21.	1.1	1.7	2.4	2.9
	1.030	27.	4.0	2.4	3.7	4.5

Table 1: The minimum root-mean-square chromatic dispersion in a w-fiber for different doping levels in the core and in the inner cladding. The unit is ps/(km nm).

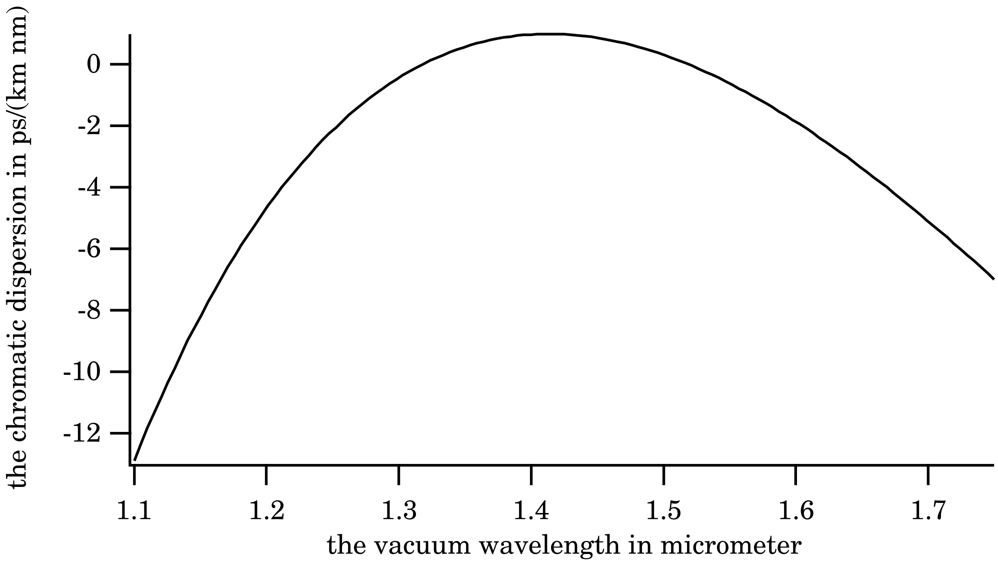

Figure 2: The chromatic dispersion for the "optimal" w-fiber $(N_1, N_2, b, a) = (1.02, 0.99, 1.91\ \mu\text{m}, 2.85\ \mu\text{m})$. The rms-value of the chromatic dispersion over the vacuum wavelength range [1.25 μm, 1.60 μm] is equal to 0.9 ps/(km nm).

2.2 Triangular-index profiles with a depressed inner cladding

The described method of investigation can be applied to similar refractive-index profiles. A normalized triangular-index profile with a depressed inner cladding is given by

$$N(r) = \begin{cases} N_1 + (1 - N_1)\,\frac{r}{b} & 0 \le r < b \\ N_2 & b \le r < a \\ 1 & r \ge a \end{cases} \tag{2.2}$$

If $b = a$ a triangular-index profile without a depressed inner cladding is obtained. The radius a yielding $\lambda_c = 1.25\ \mu$m is calculated. The cut-off condition valid for a step-index fiber can, of course, not be used. The radius a is then increased in steps and the corresponding inner radii b, yielding $\lambda_c = 1.25\ \mu$m, are calculated. This generates a curve in the a-b-plane. Minimum rms-dispersions along such curves are given in Table 2. According to this table, if the doping level in the core center is less than or equal to three per cent and the doping level in the inner cladding is less than or equal to two per cent then the minimum rms-dispersion is equal to 5.4 ps/(km nm).

		N_2				
		1.000	0.995	0.990	0.985	0.980
N_1	1.002	13.	13.	13.	13.	13.
	1.005	9.7	9.7	9.7	9.7	9.7
	1.010	6.8	6.8	6.8	6.8	6.8
	1.015	8.2	6.0	5.9	5.9	5.9
	1.020	13.	6.2	5.8	5.6	5.5
	1.025	18.	7.2	6.0	5.6	5.4
	1.030	24.	9.6	6.8	6.0	5.6

Table 2: The minimum root-mean-square chromatic dispersion in a triangular-index fiber with a depressed inner cladding for different doping levels in the core center and in the inner cladding. The unit is ps/(km nm).

2.3 Error induced by approximate refractive-index model

In order to investigate the magnitude of the error induced by the approximation (1.2) the exact chromatic dispersion of the following w-profile is calculated. The core is assumed to be 13.5 mole-percent Ge-doped silica. The inner cladding is assumed to be 1.0 mole-percent F-doped silica. The cladding is assumed to be pure "quenched" silica. The Sellmeier formulas given by Fleming [3, 4] are used. The inner radius b and the outer radius a are chosen as 2.14 μm and 3.46 μm respectively. These radii minimize the rms-dispersion for these particular doping levels. The rms-value of the exact chromatic dispersion is calculated to 6.4 ps/(km nm). The approximate refractive-index model (1.2) with $N_1 = 1.0144$ and $N_2 = 0.9965$ yields the rms-dispersion 2.7 ps/(km nm). Thus the error in the rms-value due to the approximate refractive-index model is as much as 3.7 ps/(km nm). Consequently and unfortunately, using the approximate refractive-index model (1.2) seems to be a crude approximation when trying to design dispersion-shifted fibers, compare Safaai-Jazi and Lu [7, 8].

The full vector solution of Maxwell's equations and the approximate refractive-index model yields, as already stated, that the rms-dispersion of the "optimal" w-fiber $(N_1, N_2, b, a) = (1.02, 0.99, 1.91\ \mu\mathrm{m}, 2.85\ \mu\mathrm{m})$ is equal to 0.9 ps/(km nm). If scalar analysis is employed, instead of full vector analysis, the rms-dispersion for the same fiber is calculated to 1.2 ps/(km nm). Thus the error introduced by the scalar approximation is, for this particular fiber, 0.3 ps/(km nm).

3 Conclusion

A method for calculating the minimum root-mean-square chromatic dispersion in w-fibers has been presented. The procedure is to generate all w-fibers with a certain cut-off vacuum wavelength and then find the minimum rms-dispersion by direct inspection. The method works for similar double-clad fibers such as a triangular-index fiber with a depressed inner cladding.

Since exact refractive-index data are not available it is necessary to resort to an approximate refractive-index model. Using such an approximate refractive-index model and the full vector solution of Maxwell's equations, it is found that there are w-profiles yielding a rms-dispersion less than 1 ps/(km nm). A doping level of two per cent in the core is necessary to achieve this. An error analysis yields that the approximate refractive-index model is, in this context, a crude approximation. This makes the interpretation of the numerical result difficult.

The method presented can, with other choices of cut-off vacuum wavelength and vacuum wavelength interval, be used for dispersion shifting as well as for dispersion flattening.

References

[1] B. J. Ainslie and C. R. Day, "A review of single-mode fibers with modified dispersion characteristics," *J. Lightwave Technol.*, vol. LT-4, pp. 967-979, 1986.

[2] R. Lundin, "Minimization of the chromatic dispersion over a broad wavelength range in a single-mode optical fiber," *Appl. Opt.* (to be published).

[3] J. W. Fleming, "Material dispersion in lightguide glasses," *Electron. Lett.*, vol. 14, pp. 326-328, 1978.

[4] M. J. Adams, *An introduction to optical waveguides*, Wiley, 1981, pp. 243-245.

[5] M. Abramowitz and I. A. Stegun, Eds. *Handbook of Mathematical Functions*, Washington, DC: NBS, 1964, pp. 878-879.

[6] R. Lundin, "A general power-series expansion method for exact analysis of the guided modes in an optical fiber," *J. Lightwave Technol.*, vol. LT-4, pp. 1617-1625, 1986.

[7] A. Safaai-Jazi and L. J. Lu, "Evaluation of chromatic dispersion in w-type fibers," *Opt. Lett.*, vol. 14, pp. 760-762, 1989.

[8] A. Safaai-Jazi and L. J. Lu, "Accuracy of approximate methods for the evaluation of chromatic dispersion in dispersion-flattened fibers," *J. Lightwave Technol.*, vol. 8, pp. 1145-1150, 1990.