A NOVEL APPROACH FOR OPTIMIZED DISPERSION IN OPTICAL FIBER COMMUNICATION

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ABSTRACT

A light signal propagating in an optical fiber is subject to a variety of ways in which it can get distorted. Many of these are based on different propagation velocities for different parts of the signal, resulting in dispersion. After such distortion, there is a risk that the signal arrives at the receiver in such a mangled form that it may be impossible to correctly decipher it. In this paper a novel approach for optimized dispersion using different refractive index profiles have been clearly described.

Keywords: Dispersion, W fiber, T fiber, Quadruple clad fiber

1. INTRODUCTION

No light signal is ever truly monochromatic; rather, it contains Fourier components from a certain spectral interval. In other words, a light pulse of finite duration by necessity has a nonzero spectral width. Different frequency components, however, will propagate with different velocity. This gives rise to differential transit time and thus to signal distortion called delay distortion.

The wavelength dependence of the refractive index is behind three different contributions to delay distortion. They are collectively called chromatic dispersion. Individually, they are

Material dispersion. Dm: This contribution arises directly from the wavelength dependence of the index. Material dispersion is not specific to fibers but can be found in any bulk glass. It is independent of geometry and (given the material) depends solely on wavelength.

Waveguide dispersion. Dw: In the particular geometry of optical fibers, there is a modification to the differential propagation time. The signal power is partitioned between core and cladding; the splitting ratio depends on the wavelength. On the other hand, core and cladding indices are slightly different. As the wavelength is varied, we have a crossover from mostly core index to mostly cladding index. The result is a contribution to the wavelength dependence of the effective index.

Profile dispersion. Dp: The index difference between core and cladding itself, and thus Δ, is also wave length-dependent. (Core index and cladding index do not vary “in parallel.”) This gives rise to another correction which, however, is often much smaller than material and waveguide dispersion.

Another reason for dispersive distortions in single-mode fibers is related to the state of polarization of the light. As mentioned above, each mode can be decomposed into two mutually orthogonal parts. An ideal fiber has perfect circular symmetry; then both polarization states (polarization modes) propagate with identical velocities. However, real-world glass always has at least some residual birefringence; this implies a slightly different effective index for both states. One can argue that the term “single-mode fiber” is a misnomer: Even when it is true that only a single geometric field amplitude distribution (LP01) can propagate, it still consists of two polarization modes. This is why in real fibers there is polarization mode dispersion.

So far we have dealt with fibers with a step index profile. One might note that there never is such a thing as an exact step index fiber. Due to manufacturing limitations, there are slight deviations from the ideal profile, e.g., quite often there is a central dip of the index caused by a certain process step. More importantly, fibers are often used with a refractive index profile that is more complex. When such fibers are produced, the objectives are to (a) maintain the single-mode property, (b) maintain low loss, and (c) add more design degrees of freedom for controlling and tailoring the dispersion.

In the following sections we will deal different R.I Profiles such as Graded Index, W Index, T Index, and Quadruple Clad Index & Dispersion Shifted. At last section 7 deals with conclusion.
2. GRADIENT INDEX FIBERS

In the context of multimode fibers, we have already mentioned a radial dependence of the index according to

$$n(r) = n_0 \sqrt{1 - 2\Delta \left( \frac{r}{a} \right)^\alpha}$$

(1)

Single-mode fibers can be endowed with a similar gradient index profile. Ray optics fails to provide a good interpretation in this case. A wave-optic calculation yields the following:

- $\alpha = \infty$: This limiting case is the step index profile (SI profile). The cutoff of the second (LP11) mode is at $V = 2.405$.
- $\alpha = 2$: For a parabolic profile (Fig. 1) the cutoff of the second mode shifts to $V = 3.518$.
- $\alpha = 1$: This is a triangular profile, hence the name “T fiber” (as in triangular). Here the cutoff of the second mode is even higher. As a rough approximation, the cutoff occurs at $V \approx 2.405 + 2/\alpha$.

3. W FIBERS

There may be an additional zone between core and cladding having its own lower refractive index (Fig. 2). Then a cross-sectional index profile roughly resembles the letter W; hence the name “W fiber” (Fig. 3). An alternative name is “DIC fiber” for depressed-index cladding fiber. This profile provides ample freedom for designing the dispersion variation.

Figure 1: Pseudo-3D rendering of the refractive index profile. Across the circular section the index is plotted in vertical direction.

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Figure 2: Schematic shape of the index profile of a W fiber (depressed-index cladding profile). There are three indices for core, inner, and outer cladding, labeled here as $n_1$, $n_2$, and $n_3$, respectively.
Figure 3: Pseudo-3D rendering of the refractive index profile of a W fiber (depressed-index cladding profile).
For this profile, we define a V number

\[ V = \frac{2\pi}{\lambda} a \sqrt{n_1^2 - n_3^2} \]  

(2)

And an index contrast

\[ R = \frac{n_2 - n_3}{n_1 - n_3} \]  

(3)

It is a remarkable property of this profile that in marked contrast to the step index profile which guides the fundamental mode down to arbitrarily small V

Figure 4: For fibers with W profile, V can be controlled by the index contrast. Over a certain range a linear approximation is appropriate.

Figure 5: For fibers with W profile, the cutoff behavior can be controlled through the ratio of radii b/a.
There is even a cutoff for the fundamental mode LP01 as soon as b/a is sufficiently larger than unity. For example, at R=−0.5 and at b/a=3, the fiber is single mode only in the interval 1.8≤V ≤3.0. For V ≥3.0 there is the additional LP11 mode, and for V ≤1.8 there is no guided mode at all. At least in principle – here the fundamental mode has a finite lower cutoff. Approximately and for medium values of the index contrast (Figs. 4 and 5), at the fundamental mode cutoff one has

\[ V_o \approx 1.075 (1 - R) \] (4)

Note that in the limit n2 → n3 which reproduces the step index profile, this simple linear trend is not maintained, and V goes to zero in accord with our earlier result for step index fibers.

4. T FIBERS

T fibers or triangular fibers are popular because the dispersion trend is more favorable than in step index fibers, while losses are, if anything, even lower. The latter can be traced back to the interface between core and cladding: for the sudden transition of glass composition there is an enhanced chance of mechanical stress which is mitigated by a more gradual transition. Figures 6 and 7 shows a modified T profile which is really a combination of T and W profiles.

5. QUADRUPE-CLAD FIBERS

It is possible to add more concentric cladding layers, and increasingly the number of design degrees of freedom rises in the process. Quite frequently a quadruple-clad fiber is used (see Figs. 8 and 9). The core is typically doped with germanium and thus has a raised refractive index. The first cladding zone can be doped with phosphorus and fluorine and has lowered index. In the second and third cladding zones germanium and phosphorus/fluorine are repeated with suitable concentrations. The outermost cladding can then remain undoped fused silica.

Figure 6: Schematic refractive index profile of a fiber with triangular core profile, shown with a depressed inner cladding. Again, three indices n1, n2, and n3 need to be distinguished.

Figure 7: Pseudo-3D rendering of a triangular profile, here with more complex cladding composition.
6. DISPERSION-SHIFTED OR DISPERSION-FLATTENED

There is an important distinction between dispersion-shifted and dispersion flattened fibers. In comparison to a step index fiber, by using a triangular core profile with a depressed cladding zone as in Fig. 6, one can achieve a shift of the dispersion curve toward longer wavelengths (Fig. 10). The zero dispersion wavelengths can thus be moved all the way to 1550nm if desired. Using a quadruple-clad design one can even achieve a very low dispersion simultaneously at both 1300 and 1550nm by bending the dispersion curve flat.

![Figure 8: Schematic refractive index profile of a quadruple-clad fiber. Here five indices and four radii must be distinguished.](image)

![Figure 9: Pseudo-3D rendering of a quadruple-clad fiber profile.](image)

![Figure 10: Tailoring of the dispersion curve through choice of suitable index profiles: dispersion-shifted and dispersion-flattened fiber in comparison to a standard step index fiber.](image)
7. CONCLUSION:

The motivation to tailor the dispersion curve is to get the better of two worlds the minimal dispersion of the second window combined with the minimal loss in the third window. Dispersion flattened fibers have low dispersion at both the second and third windows at the same time; such fibers can be used as direct replacement for older fiber designed for the second window but provide the added benefit of also performing well in the third window.

8. REFERENCES


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