Stored Energy, Transmission Group Delay and Mode Field Distortion in Optical Fibers

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***Abstract*—The relationship between transmission group delay and stored energy in optical fibers is discussed. We show by numerical computations that the group delay of an optical pulse of finite bandwidth transmitted through a piece of a low loss optical fiber of unit length is proportional to the energy stored by the standing wave electromagnetic field. The stored energy-group delay ratio typically approaches unity as the confinement loss converges to zero. In case of a dispersion tailored Bragg fiber, we found that the stored energy-group delay ratio decreased while the confinement loss increased compared to those of the standard quarter-wave Bragg fiber configuration. Furthermore, a rapid variation in the group delay versus wavelength function due to mode-crossing events (in hollow core photonic bandgap fibers for instance) or resonances originating from slightly coupled cavities, surface or leaking modes in index guiding, photonic bandgap, or photonic crystal fibers always results in a rapid change in the mode-field distribution, which seriously affects splicing losses and focusability of the transmitted laser beam. All of these factors must be taken into consideration during the design of dispersion tailored fibers for different applications.**

***Index Terms*—Optical fiber theory, ultrafast optics, microscopy.**

I. Introduction

DISPERSIVE properties of optical fibers play an important role in long distance, high speed optical data transmission systems [1] and in ultrashort (ps or fs) pulse optical fiber laser systems [2]. When optical fibers are designed for dispersion compensation in optical telecommunication systems, there are a few tradeoffs encountered during their design: they can be designed for a high figure of merit (FOM) or a high dispersion slope for instance the latter one being limited by the required minimum bandwidth or acceptable loss of the fiber for instance [1]. In order to minimize the loss in an optical telecommunication system, one can define the FOM for dispersion compensating fibers (DCF) as the ratio of the negative dispersion coefficient ($\mathbf{D}_{\mathrm{DCF}}$) and loss of the DCF module (α_{DCF}) [1].

Recently, we have shown [3] that reversed slope ($S < 0$) or flat ($S = 0$), anomalous ($D > 0$), or zero ($D = 0$) dispersion functions can be obtained in a wide wavelength range by introducing resonant structures in the fiber cladding in hollow-core, air-silica photonic bandgap (PBG) fibers or in solid core Bragg fibers with step-index profile. Such optical fibers could be well suited for distortion free delivery or high quality pulse compression of broadly tunable or broadband femtosecond laser pulses in all fiber laser systems, such as femtosecond pulse, all-fiber laser oscillators [2], and amplifiers [4] being suitable for nonlinear microscopy. During the last few years, novel, all-fiber, multimodal (TPF + SHG + CARS) microscope systems have been presented [5]–[7] that can be combined with endoscopy [7], which would greatly increase the utility of nonlinear microscopy for pre-clinical applications and tissue imaging [8]. Application of DCF for pulse shortening, however, might be limited by splicing losses in all fiber laser systems, or by mode-field distortions limiting the focusability of the laser beam exiting the optical fiber delivery and pulse compression system. The focused beam spot size is of primary importance in *in vivo* nonlinear microscopic imaging systems, since the highest signal level must be obtained at a minimal thermal load (absorbed average power level) in order to minimize the risk of thermal damage of the biological sample. Accordingly, when designing optical fibers for nonlinear microendoscopy, not only dispersive and nonlinear properties but mode-field distortions of the dispersion tailored fibers must also be considered. (In contrast to optical telecommunication systems, losses in these fibers are not of primary importance in most practical cases.)

In this paper, we discuss the physics behind the operation of “dispersive” optical fibers, i.e., optical fibers designed for dispersion (D) or dispersion slope (S) compensation to the second- or third-order.

In the followings, we show that the group delay (τ) of a relatively narrowband optical pulse transmitted through a piece of optical fiber of unit length is proportional to the energy stored by the standing wave electromagnetic field at the same (central) frequency, as long as the confinement loss is small. This strong relationship between these two physical quantities is not surprising at all, but has not been emphasized and used for the design of “dispersive” optical fibers. Having this relationship in mind, one can construct higher performance “dispersive” optical fibers, such as high-order mode (HOM) fibers [9], and hollow- or solid-core PBG fibers [3].

In the last section of this paper, we address the question how much the focusability of the laser beam is affected by the superimposed cladding modes present in “dispersive” optical fibers that might be a critical issue in nonlinear microendoscope systems.

II. Theory

There are two basic approaches for tailoring the dispersion of optical waveguide devices: modulating their refractive index profile along the light propagation direction or in the

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