Dispersion Management in Highly Nonlinear, Carbon Disulfide Filled Holey Fibers

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***Abstract*—We study various fiber designs which incorporate a highly nonlinear liquid, carbon disulfide, with the aim of designing a structure with the highest possible nonlinearity and at the same time a low and flattened dispersion at telecom wavelengths, as required for many all-optical processing devices. We observe that soft glass-based fibers cannot fully exploit the high nonlinearity of carbon disulfide, whereas a silica microstructured fiber with a selectively filled core allows excellent dispersion control and a nonlinear coefficient in excess of 6500 $W^{-1} \cdot km^{-1}$ at telecoms wavelengths.**

***Index Terms*—Nonlinear optics, optical fiber dispersion, optimization methods.**

I. Introduction

A LARGE number of devices for all-optical processing at telecom wavelengths rely upon nonlinear Kerr-type effects within an optical fiber. To reduce the power or fiber length requirements, fibers with a low attenuation loss and as high as possible nonlinearity per unit length (γ) are required; at the same time, to improve the performance of many processing devices (particularly those based on four-wave mixing and multiwavelength devices that are sensitive to pulse walkoff), a low and flat group velocity dispersion (D) is required. The current state-of-the art is represented by conventional dispersion-flattened highly nonlinear fibers (DF-HNLFs), offering losses lower than 1 dB/km and a very low dispersion slope (DS) of $\sim 10^{-2} - 10^{-3}$ ps/nm^2/km across the full C- and L-bands [1]. However, the nonlinearity of these fibers is around 20–30 $W^{-1} \cdot km^{-1}$ with the result that several hundred meters of fiber are still required to generate the required nonlinear phase shift at practical power levels. For selected applications, silica holey fibers (HFs) may provide a better solution, offering either a larger γ, or a wider bandwidth of low and flat group velocity dispersion [2], whereas dispersion-flattened soft glass HFs, which have recently been demonstrated [3], provide scope for a further increase in the nonlinear coefficient, albeit at the cost of substantially increased fiber loss. For all these fibers, the need to simultaneously control the dispersion limits the value of the maximum fiber nonlinearity to between one and two orders of magnitude that of conventional DF-HNLFs.

One possible way to increase γ is to infiltrate HNLFs with highly nonlinear liquids (HNLLs). Previous studies on using HNLLs in conjunction with tapers or HFs have shown that extremely high γ values of the order 2000–4000 $W^{-1} \cdot km^{-1}$ can be achieved; however, in these studies no attempt was made to flatten the fibers dispersive properties [4], [5]. In this letter, we show how different glass-based wavelength-size waveguides can be used in combination with an HNLL to generate the highest possible γ, while maintaining a low and flat dispersion in the 1.5- to 1.6-μm wavelength range.

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II. Waveguide Structures and Optimum Designs

Among the many HNLLs, mostly solvents, that have been used in the last 40 years for nonlinear optics experiments, we focus on carbon disulfide (CS_2) due to its high nonlinear refractive index ($n_2 \sim 3.2 \times 10^{-18}$ m^2/W for pulses longer than the orientational molecular response time of 1.5 ps [6]) and its good transmission spectrum which is almost free of absorption peaks in the spectral range extending from the visible to the midinfrared [5].

The linear refractive index of CS_2 at 1550 nm is $\sim$1.59. We study the possible use of glasses having both a higher and a lower refractive index than CS_2. Examples of the first category are the bismuth oxide glass (Bi), $n \sim 2.02$ and $n_2 \sim 32 \times 10^{-20}$ m^2/W and the commercially available Schott SF57 lead silicate (LS) glass, $n \sim 1.80, n_2 \sim 41 \times 10^{-20}$ m^2/W. Silica is an example of the second category, with $n \sim 1.44$ and $n_2 \sim 2.3 \times 10^{-20}$ m^2/W.

Our analysis is restricted to waveguides guiding through (modified) total internal reflection: we did not consider hollow core bandgap fibers because they would not allow the required low and flat dispersion in the region of interest, while in solid core, ARROW-based fibers the mode inside the bandgap would be predominantly guided in the glass, hence greatly restricting the benefit of the high n_2 of the liquid. Therefore, we consider three main waveguide types, shown in Fig. 1 and all possessing a high refractive index core: (a) a soft glass rod surrounded by CS_2; (b) a soft glass HF infiltrated with CS_2; (c) a silica HF with a hollow core, selectively filled with CS_2. The material dispersions of all glasses and of CS_2 are shown in Fig. 1(d). Simulations were carried out with a full vector finite element method [7], while the dispersion was optimized with a simplex method, set to minimize the objective function

$$V = \sum_{\lambda_i = 1.5\mu\text{m}}^{1.6\ \mu\text{m}} |D(\lambda_i)| \tag{1}$$

with respect to the free structural parameters. Here D is the value of the dispersion calculated at five wavelengths λ_1 between 1500 and 1600 nm. The dimensions and associated

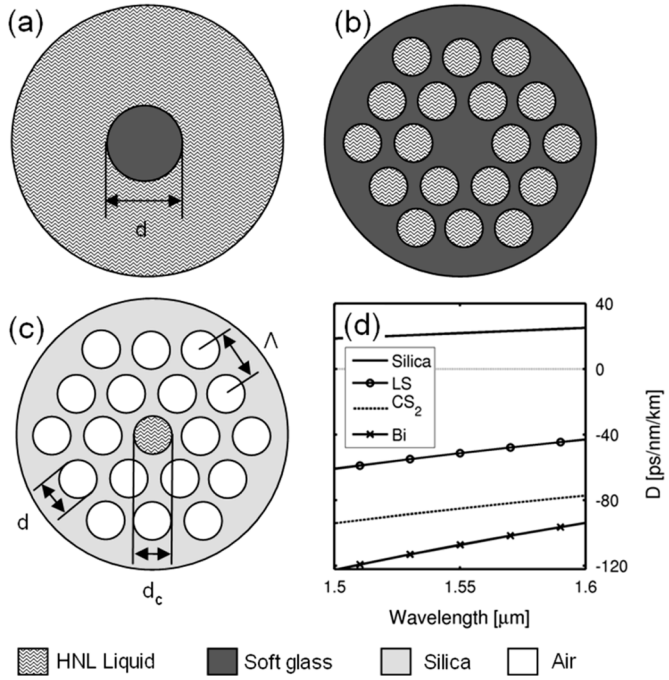

Fig. 1. Structures studied: (a) soft glass rod immersed in liquid; (b) soft glass HF infiltrated with liquid; (c) silica HF with a liquid filled hollow core; (d) group velocity dispersion of all the materials employed in the study.

TABLE I
OPTIMIZED WAVEGUIDES

	D [ps/nm/km]	DS [ps/nm^2/km]	γ [W^{-1}km^{-1}]	Power in core (%)	Dimensions
Bi rod	0.5	-0.069	1221	92	d = 1.30 μm
LS rod	0.2	0.073	546	95	d = 2.26 μm
Bi HF	0.7	0.125	827	95	Λ = 1.39 μm d/Λ = 0.92
LS HF	-4.5	0.129	371	97	Λ = 2.40 μm d/Λ = 0.92
SiO_2 HF	0.9	-0.002	6776	65	Λ = 1.36 μm d/Λ = 0.75
SiO_2 HF	0.6	0.007	6548	75	Λ = 1.36 μm d_c/Λ = 0.9 d/Λ = 0.65

summary of the main optical properties of the best structures achieved with this method are shown in Table I, whereas the corresponding dispersion curves are shown in Fig. 2.

A. Soft Glass Rod Immersed in CS_2

The single degree of freedom (core diameter d) of this simple waveguide only allows limited control over the achievable dispersion. Using the parameters shown in Table I, the best rods present a zero dispersion wavelength (ZDW) at ∼1550 nm with relatively small DS of $\sim \pm 0.07$ ps/nm^2/km, as shown in Fig. 2(a). The reduced refractive index contrast relative to the glass–air case and the need to control D, reduce the amount of evanescent field in the HNLL to only ∼5% (LS) and ∼8% (Bi), preventing significant exploitation of the high nonlinearity of the liquid. As a result, γ is only increased by ∼3% (LS) and ∼10% (Bi) with respect to the glass–air case. Note that here we use a definition of γ that accounts for the spatial distribution of the nonlinearity [8]. The fragility and long-term durability

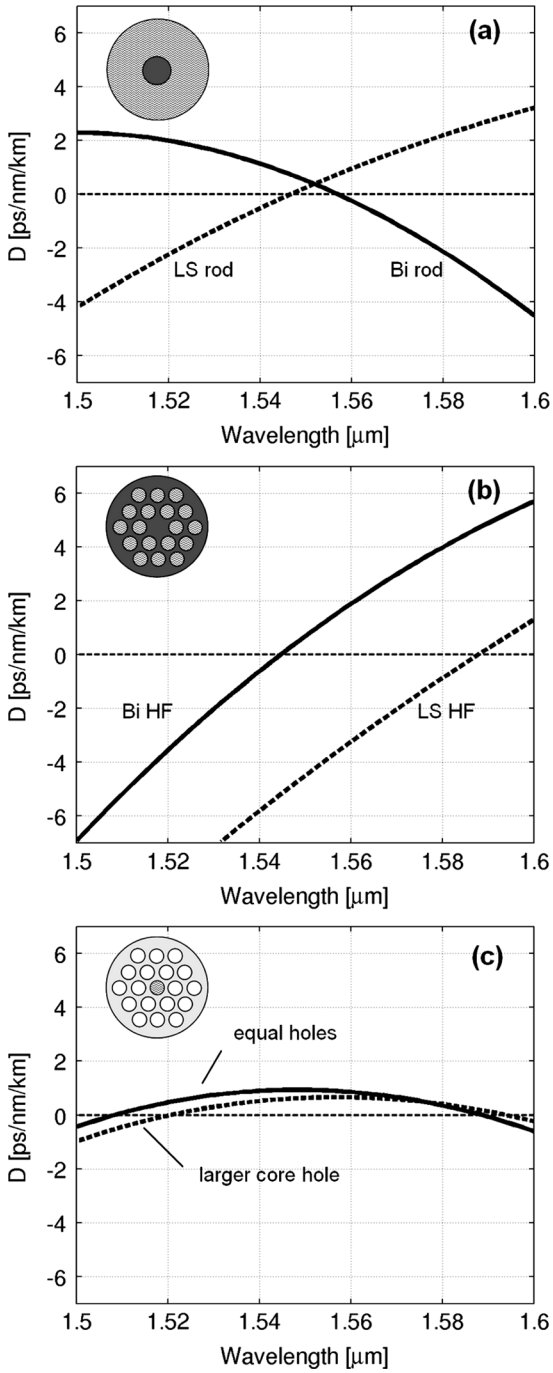

Fig. 2. Best dispersion curves for the three cases (a), (b), and (c) shown in Fig. 1.

of such small radius rods, and the limited lengths that can be fabricated are other issues of concern. However, these issues can be mitigated using a filled microstructure, such as that shown in Fig. 1(b).

B. Soft Glass HF Filled With CS_2

Despite possessing one additional degree of design freedom, we found that a hexagonal-like core shape provides a lower amount of waveguide dispersion than the circular one. From the best dispersion curves shown in Fig. 2(b) we observe that for Bi glass a ZDW at 1550 nm can still be obtained, although with

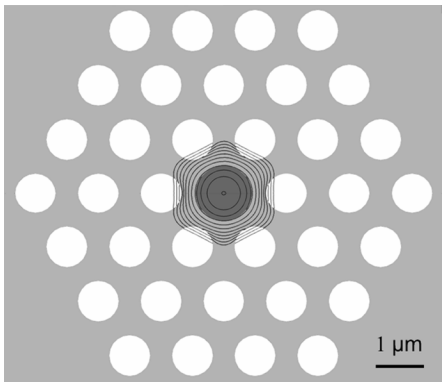

Fig. 3. Poynting vector of the fundamental mode (2-dB contour plot) for the optimum selectively filled silica HF.

nearly twice the absolute value of DS relative to case A. For the LS glass however, due to the lower index contrast between core and cladding, the waveguide dispersion contribution is insufficient to completely compensate for the material dispersion. As a consequence, the shortest ZDW that can be achieved is around 1585 nm. In both cases, we have assumed a maximum hole size of 0.92 Λ, which from our experience, we believe is close to the maximum value that can be realistically achieved for these fibers. As in the rod case, most of the power resides in the glass, and the benefit of using the HNLL is again limited to a slight increase in γ, in this case of the order of 1%–2%.

C. Silica HF With a Core Selectively Filled With CS_2

We first studied the simplest case, where all the holes, including the central one, have the same dimension. Fig. 2(c) shows that with the optimum choice of the surrounding holey cladding dimensions, extremely flat $D \approx 0 \pm 1$ ps/nm/km between 1.5 and 1.6 μm can be achieved. In this configuration $\sim$65% of the power is now concentrated in the HNLL, and combining this with the subwavelengths core dimensions, a γ as high as $\sim$6800 $\mathrm{W}^{-1} \cdot \mathrm{km}^{-1}$ is estimated.

Most selective filling techniques, either those based on the use of ultraviolet curable polymers or those based on the use of an arc-fusion splicer, rely on the presence of a differential hole size [9]. Therefore, we also studied the case of a fiber with a larger central hole, set arbitrarily to $d = 0.9\ \Lambda$. As can be seen in Fig. 2(c) and Table I, by carefully adjusting the air hole dimensions, a dispersion-flattened fiber with similar dispersive and nonlinear performance to that obtained for the uniform hole case can still be obtained. Using three rings of air holes the fiber is effectively single mode, with a confinement loss $\sim$0.2 dB/km for the fundamental mode (shown in Fig. 3), and $\sim$1900 dB/m for the lowest-loss high order mode. The loss of such a fiber is, however, likely to be determined by the absorption and scattering losses in the liquid, which, at 633 nm, were measured to add up to less than 0.3 dB/m [10].

III. Conclusion

We studied various waveguide arrangements with the aim of exploiting the extremely high nonlinearity of carbon disulfide in order to obtain a dispersion-flattened fiber with very high γ. Soft glass waveguides can allow some level of dispersion control at 1550 nm, but the waveguide dimensions required to achieve it are much larger than those analyzed in [4], preventing the build up of a significant evanescent field and greatly limiting the exploitation of the high Kerr nonlinearity of carbon disulfide. A simple effectively single mode silica HF with $\Lambda = 1.36\ \mu$m, $d/\Lambda = 0.65$ and a selectively filled core with $d/\Lambda = 0.9$, on the other hand, can combine a large modal overlap with the HNLL with a tailored overall dispersion, which is controlled by the dimension of the external air holes. Nonlinear coefficients greater than 6500 $\mathrm{W}^{-1} \cdot \mathrm{km}^{-1}$ and nearly zero dispersion (within ± 1 ps/nm/km over the full $C+L$ bands) can in principle be achieved for pulses longer than a few picosecond, justifying the more laborious preparation and some additional issues regarding the handling of these liquid-filled fibers as compared to more conventional holey or all-solid fibers. Note that such an extremely large γ is expected to decrease by nearly one order of magnitude for fs pulses, much faster than the orientational molecular Kerr effect in the liquid [6].

In addition to previously mentioned applications in all-optical nonlinear parametric devices, we also envisage applications in the field of slow-light generation, where the dispersion of the slow light pulses generated through the sharp spectral resonance of the nonlinear Raman gain of CS_2 may be accurately controlled [11].

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