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EFFECTS OF BIREFRINGENCE AND NONLINEARITY ON OPTICAL PULSE PROPAGATION IN NEW TYPES OF OPTICAL FIBERS

Final Report

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The purpose of this grant was to allow us to complete work that we had already begun on spun optical fibers and to begin studies of holey and photonic crystal optical fibers. The work on spun optical fibers was completed with great success. It led to several publications in collaboration with our co-workers at the Università di Padova, and the student who carried out this work received a major award from the Università di Padova. The work on holey and photonic crystal fibers has proceeded more slowly, but, in collaboration with Korean co-workers at the Gwangju Institute of Science and Technology, we have developed three different computational models that allow us to calculate the modes of these fibers: a Galerkin model, a plane wave model, and a multipole model. We have applied these models to the study of mode coupling in periodic gratings. In collaboration with scientists at the Naval Research Laboratory, we have also applied these models to the study of pulse compression in tapered fibers and the development of nonlinear fibers that are capable of handling large powers in high-index and chalcogenide glasses. European and Asian countries have made large investments in the development of these new glass technologies, while the United States has not. As a consequence, the United States is falling behind in what we believe will prove to be a critical area of nanotechnology. It is our view that by investing in this project, the Department of Energy has helped lay the groundwork for future development of special fiber technology in the United States, once the decision has been made that the United States cannot continue to stand on the sidelines as this technology — which appears to have great commercial and military value — is developed elsewhere.

I. Spun Optical Fibers

It has been known for some time that by spinning a fiber or by periodically rocking a fiber as it is drawn, it is possible to effectively reduce the polarization mode dispersion [1]–[4]. However, the mechanism for this reduction was not well-understood until recently. It was originally thought that the mechanism was an actual reduction in the local birefringence. (See especially [3], [4].) However, more recent work has made it apparent that the local birefringence is essentially unchanged and that the mechanism is actually periodic coupling of the fast to the slow axis and vice versa [5]–[7].

The work reported in [5]–[7] was all carried out in the short-period limit, where it is not necessary to confront the randomly varying birefringence. Our work, in collaboration with scientists at the Università di Padova, was aimed at understanding how the randomly varying birefringence in real optical fibers interacts with either spinning or rocking to determine the utility of these approaches in limiting the polarization mode dispersion. There are three scale lengths of interest in this problem: (1) the twist or spin length that determines the length scale on which the axes of birefringence change, (2) the average beat length that determines the magnitude of the birefringence, and (3) the fiber correlation length that determines the length scale on which the random variations of the birefringence cause the fiber to lose memory of its initial orientation. We carried out a thorough investigation of the system behavior, given any relationship between the three length parameters. We also compared two models for the randomly varying birefringence. These models were first introduced by Wai and Menyuk [8]. In the first model, the fixed modulus model, the assumption is made that the magnitude of the birefringence is fixed and its orientation undergoes a one-dimensional random walk. In the second model, the random modulus model, the assumption is made that the orientation and magnitude of the birefringence are described by a two-dimensional Langevin process — essentially a two-dimensional random walk with a restoring force.

Wai and Menyuk showed that these two models yield essentially the same results in fibers without spinning or rocking [8]. At the time of this early work, it was not possible to tell which if either of these models of birefringence were correct. Hence, most theoretical work has been done with the fixed modulus model, since it is the easiest physical model to analyze. Moreover, Menyuk and Wai [9] demonstrated that it is equivalent to an empirical model that was introduced by Poole, et al. [10]. Recently, however, polarization optical time domain reflectrometry experiments has made it possible to distinguish between these two models [11]–[13]. This work shows unambiguously that the only physical model to date that can account for the experimental results is the random modulus model. Thus, it has become important to analyze the consequences of the different models, and, in particular, to understand the implications of the different models in the presence of spinning and rocking.

The results of our investigations are summarized in four publications. In the first of these publications [14], we investigate limits in which a perturbation expansion is possible. In the first limit, the spin period is much shorter than the other scale lengths. In the second limit, the fiber correlation length is shorter than the other lengths, and the spin period is either shorter than the birefringence scale length or on the same order. In the third limit, the spin period is much longer than the other scale lengths. A key result was that except in the first limit, the two models yielded significantly different answers. In the second publication [15], we investigated the difference between the two Wai-Menyuk models in the limit in which the spin period is comparable to or slightly longer than the birefringence length. This limit is the most important in practice. We showed that there is a significant difference between the two models. In particular, it is possible to completely eliminate the polarization mode dispersion in the fixed modulus model, but that is no longer possible in the random modulus model. We explained this difference physically. In the third publication [16], we give a detailed mathematical discussion of the behavior in the short-period limit. Finally, in the fourth publication [17], we give a detailed treatment of all the possible regimes.

To date, there have been no careful experimental measurements that validate the theoretical predictions, although our results are qualitatively consistent with existing experiments. The difficulty is that it is difficult to control the spin period with sufficient accuracy to carry out a careful experiment. Our colleagues at the Università di Padova and the Kwangju Institute of Science and Technology have formed a collaboration whose aim is to carry out these measurements, and we are hopeful that these efforts will shortly yield fruit.

II. Holey Fiber and Photonic Crystal Fiber

Since early pioneering work at the University of Bath [18], [19], research on holey and photonic crystal fiber has become a major focus of the optics and photonics community. Sadly, research on this topic in the United States is very limited to date. However, major research groups exist throughout Europe, particularly in the United Kingdom, in Australia, in Japan, and in Korea. P. Russel [20] has summarized the most important work up to 2003 and noted some key applications. These include gas-based nonlinear optics [21], atom and particle guidance [22], and the generation of ultrahigh nonlinearities [23] and supercontinuum generation [24]. It would be nearly impossible to exaggerate the excitement that the work to date has generated and the enormous scientific and technical importance of research in this field.

Our own research has focused on the development of research collaborations with groups at the Gwangju Institute of Science and Technology (GIST) and with the Naval Research Laboratory (NRL). At GIST, they have focused on building long-period fiber gratings [25]–[27]. These gratings are created by periodically compressing a holey fiber. It has been very difficult to model the mode coupling in these fibers because it involves the interaction of core and cladding modes, and it is necessary to properly take into account the loss of the cladding modes. We did so by using a variant of the multipole method that was developed by White, Kuhlmey, and co-authors [28], [29]. This work is currently being prepared for publication. An important part of this work depended on the symmetry of the stress and strain in the glass. Here, we had to assume that the strain obeyed certain symmetry relations to obtain agreement with experiment. We expect to extend this work to carry out a detailed stress-strain analysis using the finite-element method.

At the Naval Research Laboratory, we are working with three different groups. The first group is directed by E. J. Friebele, and we are modeling a tapered microstructure fiber that can be used to carry out nonlinear pulse compression. This idea is quite old, dating back to early work by Kuehl in 1988 [30] and Chernikov and Mamyshev in 1991 [31]. An experimental demonstration by Chernikov, et al. [32] was done in 1993. In standard fiber, the mode diameter remains almost constant while the dispersion decreases. By contrast, we have found that in holey fiber, the effective mode area also changes. However, it does not change as rapidly as the taper, and, eventually, the mode leaks beyond the last ring of holes, and the loss becomes unacceptably large. This work will be presented in the 2005 Conference on Lasers and Electro-Optics, and the fibers are currently being drawn to test these ideas experimentally. In carrying out this work, we used a combination of the Galerkin method [33] with the multipole method [28], [29], which allows us to rapidly determine the mode locations and then determine the loss. The second group is being led by Brian Justus, and they are confining a mode to a small core area in a high-index glass. The goal is to guide high power light. We have determined the appropriate parameters that are needed to guide the waves, and we are discussing the extent to which they can achieve those parameters in practice and how they will have to be altered. Finally, we are modeling high-power propagation in chalcogenide glasses [34]. This work is in its very early stages.

I will note that in collaboration with a group led by S. Cundiff at the National Institute for Science and Technology (NIST) in Boulder, CO, we have also modeled polarization effects in supercontinuum generation. This work has already been published [35].

While finding sufficient external support to carry on this work is a problem, we intend to carry on this work to the extent that we can. Our view is that it is of great national, scientific, and technological importance.

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