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SINGLE-MODE, DUAL-MODE AND FEW-MODE FIBERS: A BRIEF ACCOUNT

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After the invention of LASER in 1960, the field of optics again became active. New fields , such as, nonlinear optics, opto-electronics, quantum optics etc. were born. In particular, optoelectronics completely revolutionized the conventional telecommunication technology by introducing the fiber optic communication system. In such a system, the information signal to be transmitted is coded into optical pulses. The presence of a pulse denotes bit one and absence of a pulse represents bit zero. The optical fiber contains a cylindrical dielectric core of higher refractive index surrounded by a coaxial dielectric cladding of slightly lower refractive index. The coded pulses are then guided through the core of an optical fiber to the receiving end undergoing total internal reflection at core-cladding interface. The cladding has a diameter of 125 to 150 µm and is made of pure silica. The core diameter varies typically from 5-10 µm (for single mode fibers) to 50 µm (for multimode fibers) and is made up of silica doped generally with GeO_2 to increase the refractive index relative to the cladding. Besides being used as the transmission medium, the optical fibers are also used for sensing poisonous gases, magnetic field, electric current, pressure, temperature, humidity, pesticides etc.. The fibers also find application as probe in scanning near field optical microscopes (SNOM). When doped with Er^{3+} ions, the fibers can also act as fiber amplifiers (thus replacing the electronic repeaters) and as fiber lasers.

Let us now confine our discussion to optical communication system. An optical pulse incident at the input end of the fiber excites several modes. A mode is defined as a transverse field (or intensity) distribution that propagates undistorted in form along the fiber axis with a definite propagation constant and a definite state of polarization. A fiber supporting a number of modes is called a multimode fiber. The modes excited by an optical pulse at the input end should recombine at the output end to reproduce the original pulse shape. Unfortunately this does not happen because these modes propagate with different group velocities and hence their arrival times at the output end are different although these are excited at the input end at the same instant. This results in a temporal broadening of the pulse causing a distortion of the pulse. This phenomenon is known as pulse distortion due to intermodal dispersion and is of the order of nano second per kilometer. The information carrying capacity of a system is larger if larger number of optical pulses can be transmitted per second and still be received as non-overlapping pulses at the output end. To minimize pulse distortion due to intermodal dispersion, single mode fibers were introduced in the latter half of 1970s and are in use today. In a single mode fiber, only one mode, the fundamental mode (also known as LP_{01} mode) propagates. Hence pulse distortion due to intermodal dispersion gets eliminated in such fibers.

Even in a single mode fiber, an optical pulse gets broadened due to chromatic dispersion. Chromatic dispersion can be written approximately as the sum of material and waveguide dispersions. The material dispersion arises due to the dependence of refractive indices of fiber materials on the wavelength λ of light whereas the waveguide dispersion arises due to dependence of the propagation constant β of the mode on λ. Even if laser is used, the light has a finite spectral width, however small. Thus, in a single mode fiber also there is pulse broadening due to chromatic dispersion. Fortunately, it is found that the waveguide and material dispersions have opposite signs for $\lambda > 1.3$ µm. By suitably tailoring the fiber parameters (the core radius, the relative index difference between core and cladding, the refractive index profile etc.), the waveguide and material dispersions can be made to cancel each other at a suitable λ (known as zero dispersion wavelength) resulting in zero chromatic dispersion or zero pulse distortion. Thus came into use the zero dispersion fibers (ZDF). Even if ZDF is used as transmission medium, the spacing between two successive repeaters is still limited by attenuation or power loss in the fiber. Single mode fibers with loss ~ 0.2 dB/km at $\lambda \sim 1.55$ µm (the then lowest loss fiber) were fabricated around 1979.By further tailoring the fiber parameters, it was possible to shift the zero dispersion wavelength to the lowest loss window of 1.55 µm. Such fibers are now called as dispersion shifted fibers (DSF) the use of which resulted in large repeater spacing. Gradually the repeaters are being replaced by Er-doped fiber amplifiers and this reduces the installation cost considerably.

The disadvantage of a single mode fiber is that it has an extremely small core diameter (5-10 µm) as a result of which splicing or jointing of two such fibers posed a big problem. To overcome this,

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around 1980 (J.I.Sakai et al, Opt. Lett. ,p.169, 1977; S.I.Hosain et al, IEEE J. Quantum Electron., p. 15, 1983) researchers proposed dual mode fibers in which the first two modes, the LP_{01} and LP_{11}, were allowed to propagate simultaneously. By suitably tailoring the fiber parameters, the group velocities of these modes could be equalized at a suitable normalized frequency or V number of the fiber which was less than the cutoff V of the third mode (so that only two modes propagate). Thus, in practice it was like a single mode fiber as it was free from intermodal dispersion and yet had a core diameter larger than that of a single mode fiber. Subsequently, with the development of fusion splicing technique, the splicing of two single mode fibers was no more a problem. Thus, work on dual mode fibers was discontinued.

Over the last few years, interest has grown in the study of few mode fibers (FMF) which may be thought of as a higher stage of dual mode fibers. Such fiber allows first few (three to ten) modes to propagate in it. Such fibers are mainly used in Astronomical telescopes (Corbett et al, Opt. Express, p.1885, 2009). This fiber can replace a single mode fiber as transmission medium provided that it is made intermodal dispersion free. With this aim, recently Riesen and Love (Opt. Quantum Electron., p.577, 2011) have theoretically proposed a FMF in which group velocities of first three modes (LP_{01}, LP_{11} and LP_{02}) have been equalized and the fiber parameters are such that the fourth mode remains cutoff. The fiber proposed by them is a fiber having power law refractive index profile. Using other types of refractive index profiles, we are also investigating the possibility of equalizing the group velocities of four or even five modes. Our aim is to get an intermodal dispersion free FMF so that it will have a core diameter much larger than that of single mode fiber, which is certainly an advantage. Since such a study requires knowledge of cutoff V values of various modes, we have first developed a numerical method to compute these (Behera, Hosain and Pattajoshi, Fiber & Int. Opt., p.112, 2011). Interestingly, from the calculation of cutoff V values we observe that the order of appearance of the modes is not unique. It drastically changes when the refractive index profile parameter changes. For example, for a power law refractive index profile, when the profile index q is less than 4.1, the LP_{12} mode appears prior to the LP_{31} mode and if the value of q exceeds 4.1 then the LP_{31} mode appears prior to the LP_{12} mode. On the other hand, if there is an imperfection like an on-axis dip, then for certain values of dip width and depth the LP_{31} mode appears prior to the LP_{12} mode. Thus while trying to equalize group velocities of few propagating modes, it is very much necessary to know which mode appears after which mode. Work in this direction is under progress.

Biography

"Dr. S.I.Hosain completed his M.Sc. in Physics in 1970 from Ravenshaw College, Cuttack, then under Utkal University. Taught Physics for 33 years in different Government Colleges of Odisha holding the positions of Lecturer, then Senior Lecturer and Reader (Associate Professor). During the last six years of his service, he was posted in administration where he held the position of Deputy Director and finally retired from service as Consultant-cum-Joint Director of the Higher Education Department on 31st May 2008. 1979 to 1984 he worked as a UGC Teacher Fellow in the Department of Physics, IIT, Delhi and received Ph.D. in Physics in theory of Fiber Optics under the supervision of Prof. A.K.Ghatak. Dr. Hosain attended the Winter College on Laser Physics and Workshop on Optical Fiber Communication during February-march 1988 at the International Centre for Theoretical Physics, Trieste, Italy. He spent six years in French Universities (CNRS Signal Processing Laboratory, Saint Etienne and CNRS Sub-micronic Optics Laboratory, University of Dijon) holding the positions of Visiting Professor, CNRS Associate Director of Research and Visiting Scientist in a European project. During this period he conducted research on various problems of optical fibers and planar optical waveguides such as power loss at splice, sensors, characterization techniques, fabrication of optical fiber tips etc. He also worked on Photon scanning Tunneling Microscope. Till date he has supervised five M.Phil., two Ph.D. dissertations and currently supervising one Ph.D. Dissertation, all in Fiber Optics theory. He is a Fellow of the Optical Society of India and the Co-ordinator of 'Optical Society of India Foundation Lecture Programme for Odisha'. He is also the Secretary of Orissa Physical Society. Currently he is a Visiting Faculty in Physics in Ravenshaw University, Cuttack."