Andrea Galtarossa research activity is dedicated to propagation effects in optical devices, in particular single-mode optical fibers. Mainly, the research is carried out by means of analytical and numerical methods followed, whenever possible, by experimental validations. The main topics are the following ones:

- birefringence effects in step-index single-mode fibers;
- measurement of polarization mode dispersion (PMD) in fibers and optical components;
- PMD effects in high bit rate systems;
- distributed measurements of birefringence in optical fibers by means of Polarization Optical Time Domain Reflectometry techniques;
- PMD mitigation techniques;
- design of ultra-low-PMD spun fibers;
- polarization effects in telecommunication fibers and special fibers;
- optical fiber sensors.

Some additional information on research activity of Andrea Galtarossa

Reflectometric measurement of polarization mode dispersion (PMD) in fibers and optical components.

Optical fiber links are commonly affected by polarization-mode dispersion (PMD) and polarization-dependent loss (PDL). Both PMD and PDL have detrimental effects on telecommunication system capacity, and because of this they are the object of deep studies. In particular, great efforts have been driven in the development of effective and precise measurement techniques, which have given an experimental insight of these two effects. Classical measurement techniques are based on the polarization analysis of a probe field transmitted through the link. Therefore, they require access to both ends of the link. Such a requirement may cause some practical problems—such as synchronizing the source with the receiver—especially when the two ends are tens of kilometers apart from each other.

By contrast, reflectometric measurements are based on the polarization analysis of the back-reflected portion of the probe field. As a consequence, they need access to only one end of the link, where both the source and the receiver may be placed, simplifying management of the measurement. One more important feature of reflectometric techniques is their ability of performing localized measurements of the polarization properties of the optical link. Indeed, polarization sensitive techniques have proved to be able to characterize the birefringence of optical fibers.

The photonics group at DEI have shown that several parameters can be measured by means of reflectometric techniques (in pulsed and CW configuration) like: instantaneous and mean value of PMD of the total link, instantaneous and mean value of PMD of arbitrary sections of the total link, mean value and statistical distribution of polarization dependent losses, cumulative increase of mean DGD as function of distance.

Part of the proposed solutions have been included in standard recommendations for PMD measurements in single-mode fibers.

PMD effects in high bit rate systems

Polarization mode dispersion is one of the limiting factor in the upgrade of high bit rate optical fiber systems. The effect, to the first order, is manifested by a doubling, in output, each input pulse, as the speed of propagation are different on the two orthogonal states of polarization, thus causing a group delay between them. If you extend the study of PMD also to the higher orders, it also shows that the signal has a chromatic dispersion and depolarization. This causes intersymbol interference and therefore, ultimately, an increase in the error rate. For this reason we have studied methods of assessing the impact of PMD on the systems to NX10 Gbit/s and MX40 Gbit/s, with analytical and

numerical techniques even in the presence of chromatic dispersion, non-linearity and noise due to the amplifiers. We also studied the cumulative effects of any polarization dependent losses of optical links as many optical components (isolators, circulators, couplers, filters, etc. doped fibers.) are affected by a moderated PDL.
Moreover, the photonics group at DEI have show that exists an analytical relationship between pulse spreading and PMD, developed a prototype of PMD compensator and found out the statistical properties of PDL.

Distributed measurements of birefringence in optical fibers by means of polarization sensitive optical reflectometry
The effects of optical and geometric imperfections of fibers can be described in terms of an equivalent random birefringence. As a consequence, this birefringence is the cause of PMD and its knowledge has some important and practical consequence in the design and analysis of optical fibers.
Some of these techniques, which we will call “classical methods,” are based on the polarization analysis of a probe field transmitted through the fiber link. The main characteristic of these techniques is that they require access to both the ends of the link; furthermore, since only the transmitted field is measured, information about the local evolution of the measured parameters is lost.
By contrast, the so-called “reflectometric techniques” are based on the analysis of the polarization properties of the back-reflected portion of the probe field. As a consequence, they need access to only one end of the link, where both the source and the receiver may be placed, thus simplifying the management of the measurement. But most important, reflectometric techniques may be used to perform a localized measurements of the polarization properties of the optical link.
Indeed, this is the case of the polarization sensitive optical reflectometer (P-OTDR and P-OFDR), which are based on the measurement of the polarization states of the field backscattered by the link, as an optical signal travels through it. Upon analyzing the spatial evolution of such polarization states, information about the local birefringence can be retrieved, whereas upon analyzing their frequency evolution, it is possible to characterize the PMD of the link. Theoretical studies have shown that also the PDL can be measured by means of a P-OTDR. By processing the backscattered signal provided by a polarization sensitive reflectometric technique it is possible to retrieve information on fiber birefringence.
The photonics group at DEI have proposed novel solutions to measure beat length, correlation length, spin period and spin amplitude. In addition, experimental results validated the so called random-modulus-model (RMM), confirming that birefringence in single mode fibers is usually linear since the circular component of birefringence affects the fiber only when external twist o magnetic field is applied.

Design of ultra-low-PMD spun fibers
In ideally circular single-mode fiber, there exist two degenerate modes with orthogonal polarizations. In practice, various imperfections, such as geometric deformation and stress asymmetry, break the degeneracy and the two modes propagate with different group velocities. This effect is called polarization mode dispersion (PMD) and the difference in arrival time of the two modes is the differential group delay (DGD). Obviously, for already-installed fibers, the only way to achieve PMD reduction is to introduce first-order or even all-orders PMD compensation. On the other hand, new solutions in fiber design have to be developed in order to obtain fibers with very low PMD characteristics.
Fiber spinning can be classified into two main classes, depending on the spin rate adopted (constant or variable spin rate). Variable spin rates permit better PMD behavior with respect to constant spin rates. In general, periodic spin functions are preferred.
The purpose of our work is to find analytical criteria for the choice of the optimum spinning profile; we studied several periodic spin functions that allow us to obtain a periodic and limited DGD as a function of distance in unperturbed fibers. In particular. we have shown that the most common and

viable solution to reduce and control fiber PMD consists in spinning the fiber while it is drawn. The effectiveness of the spinning process strongly depends on the spin profile applied to the fibers.
The Group at DEI has performed an extensive and original theoretical analysis of the PMD properties of these randomly-birefringent spun fibers, finding useful criteria to optimally choose the spin profile considering also the influence of cabling. Experimental validation of such results is currently being performed in cooperation with Foreign Institutions and Companies.

Linear and nonlinear polarization effects in optical transmission systems.
Our activity is focused on linear and nonlinear polarization effects in fibers and fiber links, with special regards to novel high bit-rate multi-level transmission formats. We are considering the impairments induced by polarization effects on fiber links as well as the exploitation of such effects in novel devices for all-optical signal processing. More in detail, the main activities are listed below:
- Design and implementation of novel techniques for the distributed characterization of linear and nonlinear effects in fiber links. These techniques will either be based on Rayleigh and Brillouin scattering through a suitable probe signal; they will enable the analysis of nonlinear polarization interactions among WDM channels and the consequent impairment.
- Analysis of polarization properties in legacy optical fiber links, in order to assess their ability to carry novel high bit-rate multi-level transmission formats.
- Analysis and design of novel devices for all-optical signal processing, based on nonlinear polarization effects.

Aim the work is thus devoted to exploring the theoretical aspects and the industrial applications of polarization cross-interactions among different optical signals propagating in both deterministic and random nonlinear optical media. A practical important consequence of the absolute stability of polarization domains is the polarization attraction phenomenon, whereby the state of polarization of an initially depolarized probe beam is attracted, with no energy loss, to the same state of polarization of a pump wave.
We are investigating novel device applications such as the implementation of loss-free nonlinear polarizers.

Optical fiber sensors for rock fall detection
Among the different typologies of landslides, the rock falls are the more dangerous in Italy, due to the difficulty of a temporal prediction and to the energy and velocity involved in the processes. Among the parameters that can define the behavior of a mass movement and forecast its short-term evolution, the measure of event precursors allows a prediction of the phenomenon evolution and permits the planning of an efficient early warning network.
Starting from these remarks, we are developing and testing polarization sensitive FOS to monitor elongations and vibrations in unstable rock slopes, in order to record their seismic precursory patterns that typically precede their collapse. If possible, a coherent detection scheme and specialty fibers will be adopted to increase the sensitivity and to record possible vibration-induced Doppler frequency shifts. These goals will be pursued through and accurate theoretical/numerical model-based analysis, which will take into account the generation/propagation of the microfractures and the corresponding induced waves, the coupling of such waves to the FOS and the related effects on the optical probing signal.
The research is carried out in cooperation with CNR-IRPI (Research Institute for Hydrogeological Protection, National Research Council of Italy).

Optical fiber sensor for high intensive magnetic field measurement
Polarization-sensitive reflectometry (PSR) is a powerful and versatile technique to characterize the local polarization properties of single-mode optical fibers. A typical PSR measurement consists in two stages. First, the state of polarization (or some related quantity) of the backscattered field originated by Rayleigh scattering is measured. Then, the gathered data are analyzed in the light of a proper theoretical model, so to infer information on the local polarization properties of the fiber under test. Actually, reciprocity allows to relate the properties of the fiber when traversed in a

direction, to the properties of the same fiber when traversed in the opposite direction. Specifically, if is the Jones matrix representing propagation in a reciprocal fiber, the propagation in the opposite direction through the same fiber is described by the transposed matrix. Indeed, this property is at the heart of all the PSR technique proposed so far, although it is not always explicitly quoted.
We drop the assumption of reciprocity and, for the first time to the best of our knowledge, we report both a theoretical model and experimental application of distributed PSR measurement in nonreciprocal fiber. Furthermore, by specializing the analysis to the case of Faraday rotation, we have developed an original procedure to perform distributed measurement of Faraday rotation in randomly birefringent fibers that may be very useful in measuring very large magnetic fields having amplitudes of several Tesla.

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