# Optical Fiber Sensors

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# Preface

This conference is now the sixth of the Optical Fiber Sensors (OFS) series, the first having been launched in London in 1983. Progress over the last six years has been rapid and the number of laboratories working in the field has grown significantly. In addition, the number of commercially available sensors is growing, although, as usual, not as rapidly as the wilder optimists originally predicted. The subject is now maturing significantly, yet this volume shows that there is still no shortage of bright, new ideas.

The OFS series is devoted to the most recent research developments in the field and, in most respects, leaves commercially oriented conferences to cover items closest to production. However, as the technology progresses, it is appropriate to provide some coverage of applications-oriented research and development, and more applied sessions of this nature have been included.

The standard of papers contributed to the conference has been very high this year, and it has unfortunately been necessary to reject a number of interesting papers. Those that remain, invited, contributed and poster papers, are included in this volume. The poster papers were chosen for their greater suitability for presentation to smaller groups of people, giving more scope for detailed discussion around the poster display.

The conference this year has been somewhat unusual in having allowed a much shorter time between the initial announcement and call for papers, and the subsequent deadline, and the conference itself. This has, I believe, led to a much improved topicality of papers, most of those submitted being of a very up-to-date nature. Also I would care to speculate that laboratories with a large number of potential papers to submit have probably only had time to prepare papers covering their best results. It is becoming too common an experience nowadays to attend a conference having already seen a large number of the papers in the rapid-publication monthly journals. We all hope that this will be less likely for this conference.

Whatever the outcome, I am sure you will appreciate the quality of the papers contained in this volume, and will join me in thanking heartily all the authors and members of the organising and technical committees who have contributed to the success of the conference. I owe a particular debt to Professor Ralf Kersten, who, as the European co-chairman, has relieved me, by voluntarily taking on far more than his normal share of a considerable workload, during a period when I changed my post to join a new company. This would normally be a major activity in its own right, without the additional effort of organising the technical program of an international conference at the same time!

Of course, I must not forget the tremendous efforts of Dr. Hervé Arditty, chairman of the International Steering Committee, who has dealt with the enormous administrative load of running the conference, whilst, at the same time, directing his company. Special credit is also due to the other continental chairmen, Professor Ohtsuka and Dr. Kim, who have, in a smooth and efficient way, dealt with all the duties asked of them.

With the greatest thanks to all concerned, I hope that you enjoy the conference and find these proceedings valuable as a reference book for many years to come.

Chandler's Ford, England
July 1989

*J.P. Dakin,*
*Chairman of the*
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Part I

# Components and Special Fibers

# 101 Uses for Single Mode Fiber Directional Couplers

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We will review the saga of the humble but ubiquitous single mode fiber directional coupler which is the principal means of fiber interconnection in single mode fiber circuits. Its use in interferometric sensors and sensor networks will be described. Its use in other applications areas and the interplay between these and sensor applications will also be considered. The types of single mode fiber couplers now available and their prospects for the future will be discussed. Speculations will be made on evolving or possible new forms of couplers to circumvent limitations of present types and to open new applications.

## Summary

Single mode fiber directional couplers are used to couple a propagating mode in one fiber to a propagating mode in another fiber. They are more important to the field of single mode fiber optics than the ancestors from which they derived, namely microwave long slot directional couplers, are to the field of microwaves. This is partly because in microwaves there are several types of couplers and junctions, while in single mode fiber optics the directional coupler is the only available all-fiber choice at this time.

In the beginning, about a decade ago, there were in some quarters strong concerns about the prospects for making very good single mode fiber directional couplers, even though integrated optic couplers and multimode fiber couplers had been successfully made during the preceding decade. Multimode couplers were made by mechanical lapping which, applied to the single mode case, would require working to submicron tolerances in spacings measured from the nearly invisible surface of the very small fiber core. Some ingenious methods were devised in an attempt to avoid this. However, by carefully establishing precise reference surfaces from which to measure, very high performance units were demonstrated using a lapping approach.

Today, single mode fiber directional couplers can be made routinely, although making state of the art units requires considerable skill. Of the various possible formats for single mode couplers, such as (1) etched types for simplicity of fabrication, (2) polished types for precise variable tuning and minimum power loss, (3) clamped, bonded or fused polished types for precise fixed coupling ratios and low loss, and (4) biconical fused types for high performance with minimum size in both fixed and tunable formats, the second and fourth types have found the widest use to date, with the latter predominating. Following the lead of the microwave directional coupler art, all of these couplers can be analyzed in terms of even and odd normal modes, leading to an understanding of the mechanisms of directivity, dispersion, polarization behavior and power loss.

Single mode fiber optic directional couplers were first developed to satisfy the needs of fiber interferometers and resonators for sensors, an application to which they are ideally


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suited. Sensors of this type were the first devices to employ single mode fibers because of the need for spacial coherence for interferometry, and single mode fiber components were developed for this field before a real need for them arose in the communication field. Here single mode directional couplers are used to couple waves coherently to produce interference fringes having high sensitivity to environmental measurands. The fit of single mode directional couplers to the needs of these devices was profound, allowing the construction of all fiber circuits in which the light never left the fiber, giving high stability as well as sensitivity. Here the directional coupler was a replacement for the familiar bulk optic beam splitter, which preceded microwaves, and which is also a directional coupler but not a single mode device.

With high quality directional couplers on hand, it became possible to also construct complex fiber optic networks for the interconnection of multiple arrays of sensors. A variety of ladder and lattice topologies have been employed, allowing one to make design tradeoffs between power efficiency and cross talk. Single mode fiber components and techniques for sensor networks have some features in common with fiber circuits and networks in other applications areas. These include fiber optic systems for microwave signal processing and fiber optic communication systems. As these areas develop there is cross fertilization between them and the sensor area.

The marriage of microwaves and fiber optics was pleasing in view of the historic microwave background for the directional coupler itself. One purpose was to transform and process the microwave signal, in either time or frequency domains, at higher speeds than could be done electronically. This was done by modulating the microwave signal onto an optical carrier and injecting this composite signal into a complex single mode fiber processing network. The same basic network topologies as used for sensor networks can also be employed as multi-element transversal filters for this purpose. These systems can involve cascaded arrays of large numbers of directional couplers. Information bandwidth which is difficult or impossible to handle in rf circuits becomes narrowband information and easily processed in these optical circuits, leading to enhanced levels of computations per unit time proportional to the square of the optical bandwidth. This, together with the ability to form large numbers of parallel fiber paths and join them all together with directional couplers leads to new possibilities for high data throughput rates. Filter characteristics can be synthesized using the classical general methods of electronic filtering. Fiber optic recirculating memories, another group of devices based on directional couplers, are complementary to the above ladder and lattice systems. They are transient memories with storage times from microseconds to milliseconds and beyond, which can function as buffer memories for the former devices.

Directional couplers find their way into the fiber optic communication area in several ways. They are applicable as taps and power splitters for the interconnection of multiple users in fiber optic local area networks. For serial distribution systems multiple users can be distributed along the length of a fiber bus using one or more directional couplers per user which act as taps onto the bus. For parallel distribution systems single mode tree couplers and star couplers can be constructed as cascades of individual directional couplers. The wavelength dependence of the beat length in directional couplers provides a basis for design of wavelength division multiplexers, where long interaction lengths are used in the couplers to provide wavelength resolution. Directional couplers can also be employed as multiport hybrid junctions for combining signals in diversity receivers and for coupling local oscillators to signal channels in coherent communication receivers. In all of these applications fiber couplers offer benefits of compatibility with the system fibers and very low internal dissipative signal loss. Prospects for directional couplers in communications should grow with the emergence of fiber networks for broadband services to homes and businesses, handling data or information modulated either directly on the optical carriers or on microwave sub-carriers.