Optical Fiber evanescent field components – an overlooked technology?

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Optical Fiber evanescent field components – an overlooked technology?

Manipulation of the optical signal by components in fiber networks is generally accomplished by breaking the fiber path and applying the required functionality in an alternative media, either planar waveguide or free space. There are notable all-fiber exceptions, such as fiber amplifiers, Bragg grating filters and fused biconical couplers. In general however, all-fiber solutions are difficult to integrate into more complex multi-functional modules and are limited in the functionality they can offer. A less commercially exploited all-fiber technology is the fiber evanescent field approach to component manufacture. These devices utilize the optical fiber waveguide by building the optical circuit directly onto the fiber without breaking into the fiber core. Significant potential benefits can be derived from such a minimally invasive technology – is this an overlooked technology?

Guided wave optical systems, whether for communication networks or sensors, in general utilize Silica based optical fibers to provide a passive, low loss transmission medium, offering relative immunity from the surrounding environment for the propagating wave. The optical energy is tightly bound within the core region of the fiber making it ideal for transmission, but making it difficult to modify the characteristics of the propagating wave in the fiber itself. Therefore functionality is generally applied in optical fiber networks by breaking the fiber and introducing an alternative medium either guided or free space.

Advantages from the use of alternative media for optical components are apparent in the capability to provide complex functionality over multi-channels in a compact, low cost format. Progression of such integration is analogous to the development of electronic integrated circuits from discrete component beginnings. The argument is clear when there is no alternative fiber based integratable technology, but if an all-fiber technology with the potential to provide integrated complex functionality was available would the argument for non-fiber components be as compelling?

System functionality

System designers require optical modules to perform specific functions or complex combinations of functions. Qualifying technology platforms should be able to produce a majority of the functional requirements.

Such requirements can be divided into essentially three general groups which facilitate full control of the optical signal: Power, wavelength and polarization, control. The table below identifies specific functions within each area which have families of components with specific parameters associated

Power control	**Wavelength control**	**Polarization control**
Generation – sources Detection – photodiodes Power splitting Switching Modulation Amplification Attenuation Power monitoring	Filtering Mux./Demux. Dispersion compensation	State of polarization control Polarizing Depolarizing PMD compensation Stokes parameter measurement

All-fiber components

All fiber components are directly compatible with the transmission medium, without the necessity for precision alignment and fixing to different materials therefore not incurring the mismatches associated with alternative approaches. In general this provides four major benefits, reduced reflection, low insertion loss, minimized PDL and similar effective operational bandwidth.

Drawing on the inherent advantages of incorporating all-fiber components several all-fiber technologies are currently utilized in systems to provide specific functions:

- Fiber doping to give amplification properties
- Fused taper couplers for power splitting, wavelength and polarization differentiation
- Bragg gratings for filtering, dispersion compensation

Discrete fiber evanescent field devices are also currently used, primarily for polarizers, VOAs and power monitors, however this particular technology platform has the potential to extend beyond simple discrete components to offer benefits normally assigned to planar waveguide and similar technologies. The rationale for this is that the evanescent field device is constructed on a fiber waveguide substrate.

Evanescent field devices

To satisfy Maxwell's equations for a dielectric waveguide the field of a propagating wave contained within the central core extends beyond the core cladding interface decaying exponentially from the interface into the cladding. The magnitude of the field in the cladding is dependent on the characteristics of the waveguide and the wavelength of the wave. Optical fibers are circular cross section dielectric waveguides and modifying the cladding material close to the core interface, within the evanescent tail, changes the guiding characteristics and consequently the propagation of the wave. Therefore the optical wave can be manipulated whilst in the fiber, by local modification of the cladding.

If the evanescent field can be accessed effectively, components can be fabricated using standard optical fibers as the base substrate without breaking the fiber core, giving a minimally invasive manufacturing method.

The evanescent field can be accessed within the fiber through several techniques including;

- Tapering at high temperature, which is the basis of the fused coupler
- Etching to reduce the whole cladding diameter leaving a fragile fiber length
- Laser processing to remove 'notches' from the cladding
- Fabricating the fiber to allow easy access to the evanescent field, e.g. D-type fiber, side-hole fiber.
- Side-polishing to remove a region of cladding from one side of the fiber.

Whilst it is acknowledged that the fused taper technique is used extensively in the fabrication of fused couplers and derivative components, side-polished devices are explored here because of the wide range of component options the technology facilitates and its potential to progress beyond the single discrete component realization to hybrid and all-fiber multi-functionality and multi-channel integration.

Side-polished fibers

Side-polishing of optical fibers was first explored during the late 1970's, primarily for coupler and polarizer applications in fiber gyroscopes. Conventionally the fiber is set in a slot cut into a substrate block on a large radius. The combined fiber and block are first ground and then polished to within a few microns of the fiber core to access the evanescent field. Although labor intensive and time consuming to fabricate, this approach enabled the investigation and demonstration of a range of functional components showing high quality performance appropriate for optical fiber systems.

Development of polishing methods such that only the fiber was ground and polished made the fiber processing simpler and far more flexible. The processed fiber is a substrate from which a predetermined length of cladding is removed to a defined depth exposing the evanescent field onto which the optical circuit can be built to provide the required functionality, figure 1. Processing by this method gives a surface parallel to the fiber core over a region which can be selected during polishing.

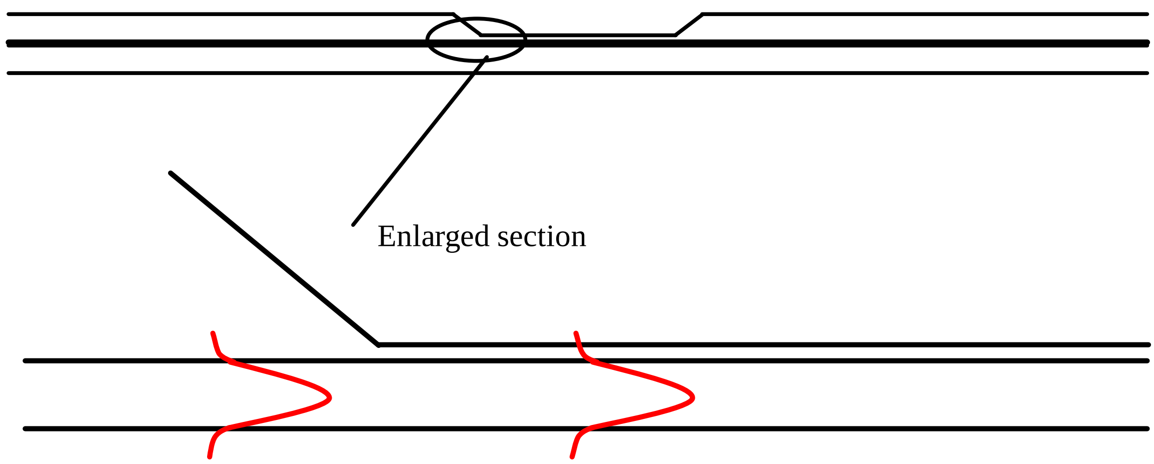


Figure 1 Schematic of processed fiber showing flat region for access to evanescent field onto which the desired functionality from the component can be built.

The side polished fiber is simply a waveguiding substrate fabricated from conventional fiber in a single process which can be compared with a typical planar waveguide requiring multiple processes to reach an equivalent stage and still requiring precise alignment for fiber pigtailing.

From the processed substrate, components can be built based on three generic classes:

- Devices with a bulk material overlay which couple to radiation modes
- Devices which have multi-layers built above the core to tailor the characteristics of the propagating wave.
- Devices which have multi-layers above the core to couple to a second waveguide, either planar or more commonly a second fiber.

Replacing the cladding with an alternative material produces attenuation proportional to the refractive index of the new cladding. Figure 2 shows the response of a substrate with the cladding removed to different distances from the core/cladding interface. The solid lines are theoretical and the points measured data. By varying the refractive index of the replaced cladding the processed region of fiber can be controlled from a guiding condition to a non-guiding condition, this forms the basis of the VOA which operates on the transitional curve and the shutter which operates between guiding and non-guiding.

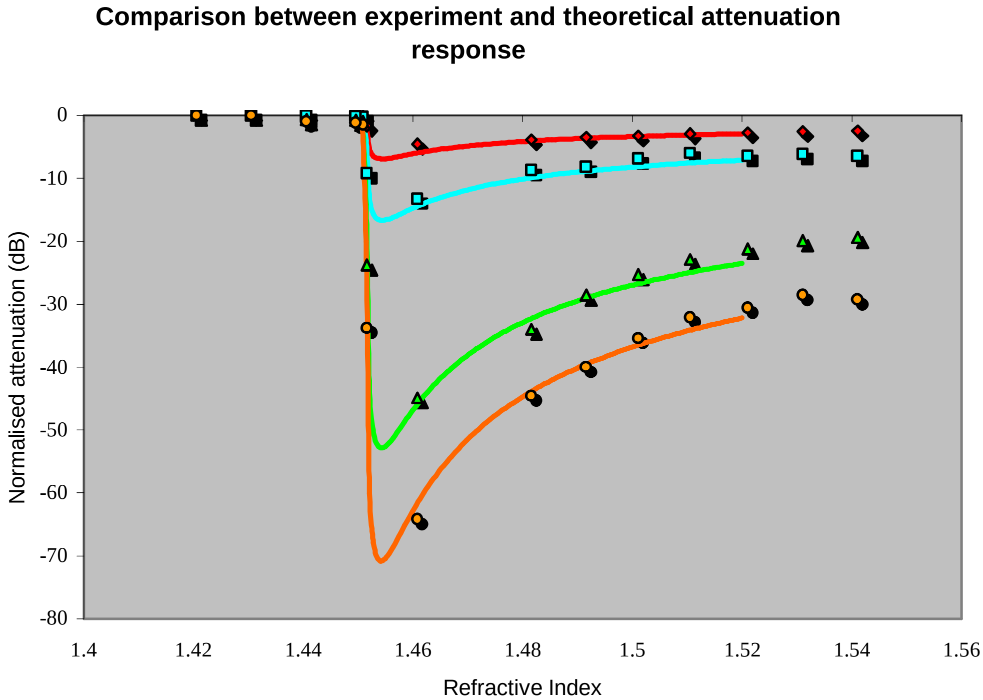


Figure 2 Theoretical curves and actual data for side-polished fibers of different depths with varying refractive index overlay cladding.

Replacing the cladding with a material such as a metal layer gives a polarization selective response, giving the basis for very high extinction ratio polarizers and stable PDL emulators. Figure 3 shows the extinction ratio of a device across a range of wavelengths. This technology produces exceedingly high performance polarizers.

Couplers are fabricated by aligning the cores and fixing the fibers together. Fusing the polished, without taper, fibers gives a robust coupler for high temperature operation and polarization maintaining fibers.

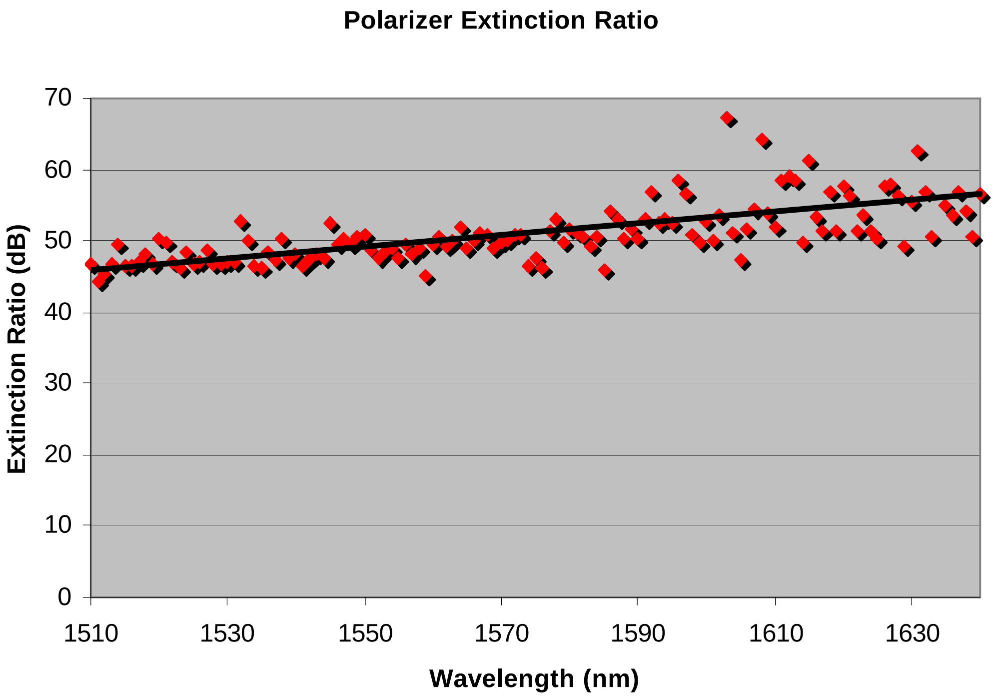


Figure 3 Typical extinction ratio response for an evanescent field polarizer (Increased spread of data at high extinction ratios is due to limitations of measuring polarimeter).

Component types

The technology offers a very flexible method to fabricate fiber components with a wide variety of functions. The table below indicates component groups that have been demonstrated in R&D laboratories and those which have been commercialized. Within each group of component type there are generally a family of components.

Component type	**R&D demonstration**	**Commercial**
Polarizer	**X**	**X**
Coupler	**X**	**X**
VoA	**X**	**X**
Power monitor	**X**	**X**
Filter	**X**	
Switch	**X**	
Modulator	**X**	
Amplifier	**X**	
Power limiter	**X**	

The range of components feasible with the technology stems from the fact that the optical circuit is built onto a basic fiber substrate, the interaction is through guiding rather than breaking into the core to access the optical energy. All the key functions have been demonstrated utilizing this technology base– switching, filtering, routing, polarization filtering, modulation, in-line power detection.

Fiber evanescent field technology offers the following potential and for some components (e.g. polarizers) demonstrated advantages for discrete components:

- Operation by guiding modification
- Match with fiber transmission medium
- Low loss
- Wide bandwidth
- Virtually no reflection
- Non-invasive to the core
- High power handling
- No pigtailing required

Examining the technology as a basis to produce discrete components shows there are several specialized components which have been developed and exploited primarily in the sensors and test & measurement markets, but the full potential of the technology has not be exploited.

Optical component technology is perceived to be analogous to electronic technology development, eventually with seamless interfacing between the electron and photon parts of the circuit. The ultimate goal is to have a common platform for full integration providing, compact, low cost, multi-functionality, multi-channel optoelectronic modules. Key drivers to achieve this are: integration, manufacturability, and reliability. Does the fiber evanescent field technology compete in these areas?

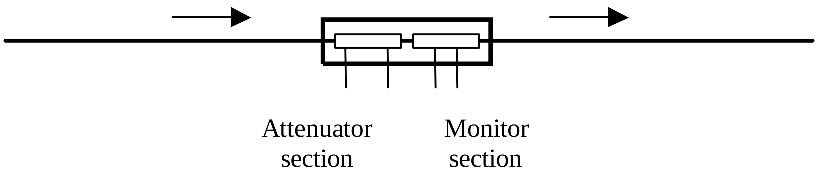
Integration

All-fiber

In general, all-fiber technologies offer a single functional component and fabrication of complex modules requires splicing and organization of lengths of fiber between the components to avoid excessive bending. Consequently, all-fiber component 'integration' can be complicated to achieve, labor intensive and results in extremely large footprint modules compared to media such as planar waveguide or MEMs technologies which can be readily processed in compact formats.

However, fiber evanescent field technology is a fiber waveguide substrate approach onto which functionality is built. Several functions can therefore be applied along a relatively short length of fiber. An example of a dual function module is a VOA with power monitor, in which the light in the fiber core can be attenuated by adjusting the voltage and the level of power in the fiber detected by a photodiode attached to the fiber substrate. The photodiode can be used to generate an error signal to control the attenuator thereby maintaining a constant power in the fiber. Figure 4 shows open loop results from a prototype device, showing the correlation between the current output from the power monitor and the current applied to the attenuator. Such a device will remove intensity fluctuations including PDL from the device and introduced by components prior to the VOA. The limit of intensity stability is determined by the PDR and the electronic control loop. Processing the fiber to produce a waveguide substrate enables this multi-functionality to be achieved in small dimensions comparable with other integration methods.

Prototypes developed to date show the feasibility of creating multiple functions along the fiber in a compact format where the fiber dimensions define integrated module size. The techniques allow extension to incorporate further functions along the fiber substrate. This capability clearly differentiates the technology from other all-fiber approaches for which integration involves splicing together a series of discrete components.



Schematic of all-fiber integrated, spliceless VOA/power monitor, unpackaged device length approximately 10mm.

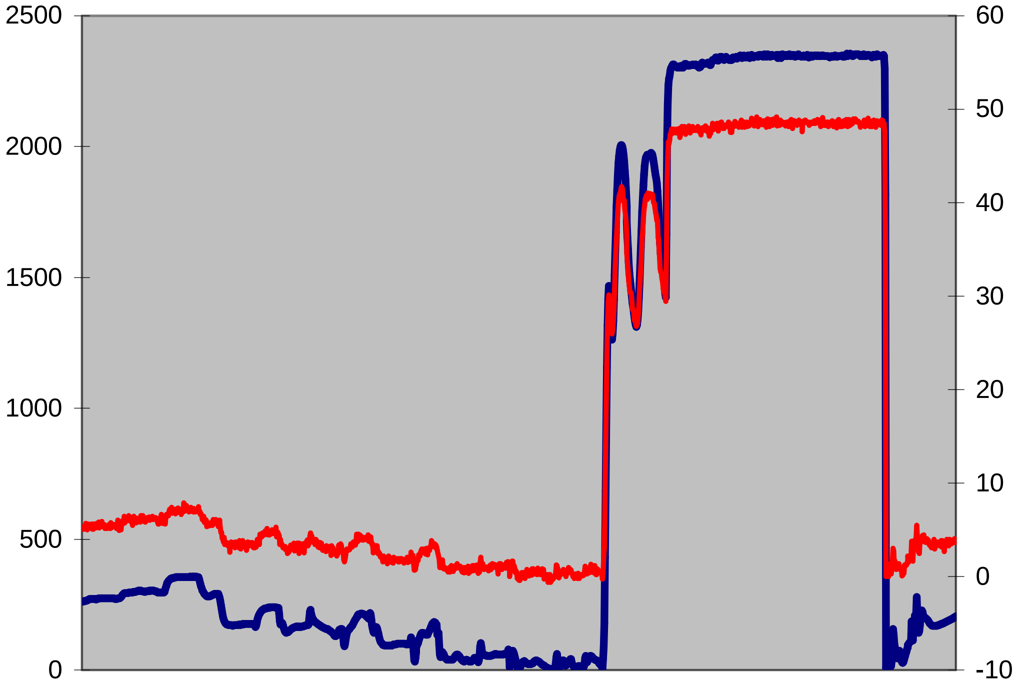


Figure 4 Integrated VOA power monitor response showing tracking of in-fiber power level by the monitor as the attenuator is adjusted.

Hybrid

Different technology platforms bring specific advantages to assist the designer. Regardless of technology choice the fiber platform is always in place i.e. all components are pigtailed to interface with the system. Component fiber pigtails are passive, however some functions are optimally achieved in the fiber and active or smart pigtails can be fabricated within the module giving a hybrid integrated unit. Several examples in which passive fiber pigtails are currently connected to components and could be readily replaced by 'smart' tails for integration into a single module are outlined below are outlined below.

i) AWG arrays are interfaced with an array of fibers to demultiplex channels, the individual fibers of which are connected to further components to perform functions such as add/drop. Hybrid integration of evanescent field fiber technology using ‘smart’ pigtails can provide a lower loss solution.
ii) Modulators/SOAs/VOAs often have requirements to monitor power to provide a control signal. The critical parameter is the level of power in the fiber following the device. Fiber power monitors can be fabricated onto the pigtail to provide information.
iii) Transmitters/receivers require control of power levels and protection against high optical power. Fiber shutters and VOA’s provide high isolation and can be incorporated into the fiber tail.

Manufacturing

Cost is a major factor for the system designer and the component price is determined by the materials and manufacturing costs. For fiber evanescent field devices the basic materials costs are minimal, the major cost is in manufacturing, specifically labor cost. The original processing method requiring mounting into a support block and polishing the combined unit, was not only inflexible but the multi-stage processing was very labor intensive, highly skilled work, low capacity and poor yield.

Processing methods have been refined considerably and manufacturing techniques adopted to address the short comings of the early research laboratory processes to produce a cost effective manufacturing process.

i) The process requires low capital investment
ii) From a well defined process unskilled operators can be trained very rapidly
iii) Production capacity per operator is adequate to maintain low cost base
iv) Production yield can exceed 95%
v) Simple, low-cost semi-automation has demonstrated a major increase production capacity.
vi) Production capacity can be rapidly increased with low capital and space requirements.

This has been demonstrated in a production environment and shown to provide low cost discrete components. Processes developed are appropriate for further automation giving higher yield, reliability and capacity. The flexibility of the manufacturing process to respond to capacity changes rapidly without cost penalty means that low cost production can be achieved at all quantity levels. Capital investment required for alternative technologies and design change costs limit realization of cost benefits of alternative technology approaches to large quantity supply.

Manufacture of fiber evanescent field components is not the barrier often perceived. Production can be automated and costs reduced by adoption of best practice production methods. Certain advantages are realized by the low cost and rapid production capacity increases achievable and although certain economies of scale are achievable, low cost manufacturing can be made at low and medium quantity levels.

Additional benefits

Availability of higher power sources and increased channel usage shows a movement to much higher in-fiber power levels. Component interface mismatches and components introducing loss centers become a problem, material definition and thermal control are of critical concern. The fiber evanescent field approach modifies the guiding properties and unwanted power can be dissipated in the appropriately designed packaging, for example in VOA's/shutters attenuation is achieved by coupling light to the radiation modes which then dissipate in the packaging. No loss center is applied in fiber and the thermal effects can be more appropriately handled outside the functional part of the component. There is very little absorptive loss in the component and the virtually no interface mismatch.

Power monitors can be designed such that the amount of cladding removed can be adjusted to ensure the level of power tapped from the fiber is sufficient to remain below photodiode saturation.

Using the same manufacturing techniques, these devices can be made using polarization maintaining fiber, multi-mode fiber and fibers with different core sizes and different operational wavelengths.

Discussion and summary

Fiber evanescent field technology is based on the fabrication of a localized waveguide substrate from a conventional fiber to access the evanescent field without impinging the core. The substrate is small, defined by the fiber dimensions and the required functionality can be constructed onto the fiber by structuring to vary the guiding conditions in a controlled way. A wide range of component functions have been demonstrated with this technology. This base substrate fuses the benefits of readily integrated technologies such as planar waveguides with the advantages of all-fiber components.

Most all-fiber technologies are appropriate for discrete components, but cannot be integrated effectively for more complex modules. To meet market demands, acceptable technologies must be able to progress in complexity of functionality offered within a compact footprint and low cost which forms the basis of a integration friendly technology. The fiber evanescent field technology fulfils this requirement and can have a role to play in complex modules.

Primary benefits can be realized in low cost small to medium quantity production and for hybrid integration with the use of 'smart' pigtails.

To a certain extent the technology has been overlooked, probably because it is perceived to be appropriate only for specialist, discrete components, and the full potential to extend beyond specialized components has not been exploited to date. However, it has not been completely overlooked, there are a few small companies commercializing specific components based on the technology, but the potential of the technology is not fully understood and has not been fully evaluated. It can offer an elegant solution to many system requirements and is potentially a disruptive technology platform.

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Phoenix Photonics Limited is one of the few companies commercializing fiber evanescent field technology. Dr Ian Giles has been involved in the research, development and commercialization of fiber evanescent field components for over 20 years and he examines the unexploited potential of this powerful technology.