FIBER-OPTIC PASSIVE COMPONENTS FOR FUTURE SYSTEMS

by

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Abstract

As fiber proves its worth in a variety of cable TV system architectures, system engineers can make greater use of fiber-optic wavelength division multiplexers, splitters or couplers, and directional coupler taps to reduce costs and provide for increased system utilization and expansion in the future.

This paper will focus on the basics of coupler technology with specific explanations of the functional parameters that need to be specified when purchasing these components. The presentation also will discuss the reasons for this emerging trend, specifically geared to the needs and interests of cable television operators.

I. UNDERSTANDING COUPLER TERMS AND PARAMETERS

Before looking at how cable TV systems can use various types of couplers, it is important to understand the basics of couplers and a little bit about how they are made.

Couplers come in many shapes, types and flavors. Luckily, they can be grouped into a few basic categories:

- Trees or Even Ratio Splitters: Power is evenly divided into, or combined from, two or more ports.
- Variable Ratio Directional Couplers or Taps: Power is unevenly split or combined between two or more ports.
- Multiplexers/Demultiplexers: Power is combined or separated according to wavelength (frequency) of light.
- Stars: Light from two or more inputs is combined and then split into two or more outputs.

As we will discuss later, these types of couplers can be used as discrete components, or several can be combined in one location to provide multiple capabilities over a single fiber.

Coupler Parameters

The most important functional parameter for any coupler, regardless of its type, is insertion loss. Insertion loss, usually expressed in dB, is how much optical power is lost from the transmission system when the component is added to the system. It refers to the total optical loss from an input port to an output port. In order to make an informed choice when comparing devices, it should be noted that insertion loss is not necessarily specified the same way from one manufacturer to another.

True insertion loss should be specified over the operating passband of wavelengths of the system, rather than at one nominal wavelength value. Many devices have what appear to be very low losses at a nominal wavelength, but exhibit somewhat higher losses over the wavelength range where systems typically operate.

This can be hidden by specifying a second term, such as wavelength dependence or coupling ratio tolerance. Both of these approaches are misleading to the user because optical power budgets are calculated in dB; the user, who must make the conversion anyway, often is surprised to find the true insertion loss is higher over the passband than originally thought. The loss over a passband is essential because optical sources are never sold or specified for applications at a single wavelength. Laser sources of the type used for cable television AM transmission often are specified with a nominal distribution of ± 10-15 nanometers (nm) from a nominal wavelength, with an additional allowance of about 5 nm shift in the device operating wavelength over time, due to aging and temperature-induced change.

In addition to insertion loss over a passband, a prospective coupler user also should insist on a true maximum loss specification, rather than an average or maximum average insertion loss. Devices that are specified by averages seem to have a number that appears as a lower loss. The prospective buyer should remember that half of the couplers he or she buys will have losses higher than the specified number, perhaps with no real limit on the upper bound. Couplers specified to a maximum insertion loss over a passband is the specification method most friendly to users, and most compatible with the way couplers are used in real life.

After insertion loss, the parameter of most concern to cable TV systems is backscattering. Backscattered or back reflected light is optical power that is reflected by the device back toward the optical source on the input fiber. In many systems, especially AM cable TV transmission with narrow optical linewidth Distributed Feedback (DFB) lasers, the backreflected energy can cause the source characteristics to change. This results in more system noise or signal distortion. There are two ways backscattering should be considered: backscattering inherent to the device, and backscattering at the fiber pigtail to system joints. The inherent backscattering characteristic of the device itself is measured with all ports but one terminated optically in index-matching gel. This is done so that the backscattering measured is due only to the performance of the coupler itself, rather than a reflection from a fiber end.

When the coupler is installed in a working system, the pigtails either are fusion spliced or connectorized. Either way, the amount of light reflected from the fiber-to-fiber joint usually is much more than the light reflected from the coupler. For most couplers available today, the backscattering is specified to be better than -40 dB. This level of backscatter will not functionally degrade a system's performance.

Some applications will use bi-directional transmission over a single fiber. When two signals are transmitted at the same wavelength, a 1x2 coupler is used to split light between the transmitters and receivers as shown (Fig. 1). In this application, low backreflection is important throughout the optical system, but directivity also is an important factor. The directivity refers to the amount of light going out an adjacent port in the non-coupled direction. In figure 1, this would be the amount of light going from the transmitter, shown attached to Port A, through the coupler to Port B. Typical coupler directivity numbers are well below 40 dB from the input signal.

Another approach to bi-directional transmission over a single fiber could involve the use of two wavelengths, transmitting in opposite directions, or a combination of the two techniques above. In these cases a multiplexer/demultiplexer type of coupler is used. These couplers, known as WDMs, combine or separate signals by their wavelengths of light. The analagous device in the electrical world combines the function of a bandpass filter and a mixer. The functional limit to system performance is known as crosstalk. Crosstalk is the amount of light seen at a port where it is supposed to be blocked. Near-end crosstalk is where light from the transmitter can interfere with the adjacent receiver. Far-end crosstalk occurs where misdirected signals from the wrong wavelength could interfere with a distant receiver's operation. Like insertion loss above, it is essential to specify crosstalk over the passband of operation, rather than at a single wavelength.

As important as the optical characteristics of a coupler are, environmental and mechanical robustness should not be overlooked. Coupler insertion loss, usually in the form of coupling ratio, can change over a range of operating temperatures. Figure 2 shows the change in insertion loss of an achromatic single-window Corning™ coupler during repeated cycling between -40°C and +85°C. Note that the graph is blown up in size so that each division represents 0.1 dB change. Changes in insertion loss over the operating window of less than 0.2 dB are considered acceptable for environmental performance. Although each coupler application may not demand such rugged performance, the general trend is toward less sheltered, outside plant passive-network applications. This trend will mean that tomorrow's devices, many of which are being installed today, will have to operate over a wider range of temperatures, environments and optical passbands than ever before. Table 1 shows an example of typical parameters to be specified for a 1 x 2 splitter and a 90%/10% variable ratio directional coupler.

The potential quantity of couplers required to satisfy widespread fiber network implementation may present the most significant challenge to the industry, however. With hundreds of millions of potential subscribers worldwide, the implementation of fiber-based distribution networks will require industrialization of passive components and opto-electronic components and systems on an unprecedented scale. In fact, fabrication technologies must be optimized for high-volume production of higher-performance components, while ensuring quality and reliability.

II. TECHNOLOGIES FOR COUPLER MANUFACTURING

Over the years, a number of coupler manufacturing technologies have been developed by industry. While techniques and capabilities are diverse, fabrication technologies have not been amenable to large volume manufacturing. The challenge to manufacturers is to deliver in large volumes high-performance products such as low-loss achromatic (wavelength-indepedent) multi-window devices required by future coupler-intensive fiber-to-the-subscriber architectures.

Fused biconic taper

The most common manufacturing technique now in use is the fused biconic taper (FBT) technology. Two fibers are axially aligned, heated and then stretched until they become joined in a thin cross-sectional region that permits light to travel from one fiber to the other (Fig. 3).

The thin coupling structure typically is affixed to an intermediate package with epoxy to prevent mechanical strains on the coupling region. An external package over the coupling structure protects the coupling region from moisture and other environmental and mechanical effects. Additional packaging may be required to provide strength/retention for the fiber pigtails.

The FBT technique is best suited for the manufacture of couplers that display low losses at a discrete wavelength or over a narrow wavelength range, typically +/-10 nm (narrowband). FBT couplers generally have not met the achromaticity requirements of future networks. However, recent work on FBT couplers has improved their performance somewhat. Double window couplers operating at 1310 nm and 1550 nm can be fabricated by etching or tapering the fibers prior to fabrication, but this additional process step adds expense and complexity to the production process.

A variation of the FBT process recently developed by Corning addresses many of limitations of the single-mode FBT process. In this method, the coupling region of the fused fibers is embedded in a specially fabricated low-index glass, creating a hermetic seal. This larger, more robust coupling region results in a device more resistant to environmental and mechanical conditions.

This simpler process yields low insertion loss without the need for pre-etching or tapering the fibers in order to control double-window optical performance. Control over the fiber and sealing glass compositions allows fabrication of various product designs with precise optical characteristics.

Fusion technologies can, within practical limits, join only two fibers at a time with the required control of optical performance. Higher-order 1xN devices are made through a process of sequential splicing, or cascading and repackaging 1x2 couplers. Aside from the increased component size, the optical performance of the resulting devices is somewhat compromised by the splices.

Planar fabrication

Recognizing the inherent limitations of standard fused biconic technologies, another very different fabrication process is gaining interest.

Fabrication technologies are being implemented to produce couplers that meet the optical performance and mechanical requirements of future systems architectures, as well as volume demands by making an optical circuit in a planar piece of substrate material.

Couplers are produced much like electronic integrated circuits using standard photolithographic techniques to transfer mask patterns of numerous coupler structures onto a wafer. The substrate wafer can be made of glass, silicon or a Group III/IV compound (Fig. 4). The wafer then is processed to create actual waveguides in the pattern of the mask structures. The processed wafer is cut into discrete coupler chips, to which fiber pigtails are added before packaging in rugged housings suitable for outside plant use.

The optical guide profiles in the substrate generally are created by diffusion or material deposition processes. Corning and other companies have developed planar technologies using ion exchange techniques to create the waveguides. Others, such as Photonic Integration Research Incorporated, employ chemical vapor deposition techniques.

Calling on its engineering and production technology base from working with glass and its raw materials, Corning has developed a planar fabrication technology that creates optical waveguides in a glass substrate. The process yields optical circuits of varying complexity in a small, monolithic sealed glass structure.

Based on this ion-exchange planar technology, planar couplers are being developed in a number of designs, including single-mode 1xN tree couplers. The design of these units produces inherently low and level optical losses over the complete range of wavelengths planned for cable television fiber-based subscriber distribution systems, because true Y-branching of the light is used. Figure 5 shows the optical performance of a 1x2 coupler from 700 nm to 1660 nm. The solid line segments represent the three passband ranges that are likely for each operating window in future services applications. As shown, the coupler can operate simultaneously in the three bands. Within each band, insertion loss is constant across the operating window.

The coupling ratio of a planar Y-branching coupler, i.e. the ratio of power split between output ports, is uniform and remains consistent across the passbands, even in the 850 nm wavelength region where the guides actually are multimoded. However, in the case of short wavelength operation, some cautions apply. The use of highly coherent sources should not be used or modal interference effects can occur in the system.

Non-coherent sources such as LEDs or self-pulsating coherent laser sources do not exhibit these interference effects. Therefore, the coupler is compatible with combinations of current and planned source wavelengths.

Devices with multiple output ports on a single small piece of glass can be made through passive integration of sequential Y-junctions (Fig. 6). Using the approach, tree couplers with any number of output ports can be fabricated.

In addition to manufacturability in large volumes, planar-based couplers offer the potential to integrate several coupler functions into a single chip, resulting in a smaller overall package. For a 1x8 coupler, the size difference between a planar device and a packaged set of cascaded fused devices can be as much as 10 times or more (Fig. 7).

Having a wide variety of low-cost devices from which to choose is important to facilitate the implementation of a variety of architectures. Each architecture places a unique set of demands on coupler performance.

III. APPLICATIONS FOR CABLE TV

The specific requirements of cable TV transmission fit very well with the concepts of passive splitting of optical signal power. The cable TV world has pioneered coaxial/electrical technology from infancy to just about its maximum potential. Perfection of the coax tree and branch architecture has been a technological challenge well met. The next generation cable TV systems will be looking to do the same with lightwave technology, and passive optical components promise to play a major role.

Together, the industry can originate some creative ideas to optimize system performance while minimizing costs. The eventual objective is bringing the specific advantages of optical transmission deeper into the system and closer to the subscriber. Much of this early thinking has been done by telephone companies in their fiber-to-the-home drive. However, the telco imagination has been constrained by their existing service commitment to provide as much upstream capacity as downstream, and a copper-wire architecture that required a "hard-wire connection" to every customer, resulting in their existing real-estate commitments .

The earliest fiber architectures that emerged were star-structured designs with dedicated individual paths between each subscriber and his or her switching center. Economic analyses quickly pointed to the cost advantages of sharing the most expensive network elements, primarily the electronics, between several customers. An underlying trend in present and emerging designs for optical distribution systems at the trunk level and beyond (what we will call fiber-beyond-the-trunk or FBTT for simplicity's sake) are architectures using fiber-optic splitters or couplers to share electronics among many users. The common thread is the extensive use of passive optical components to reduce total installed system costs and allow for future system evolution.

Coupler-Intensive Architectures

The most coupler-intensive FBTT architectures currently under consideration fall into two generic categories: active and passive stars.

Active star FBTT architectures most often use intermediate electrical-to-optical (E/O) and optical-to-electrical (O/E) conversions to capture, remodulate and transmit signals to create channels actively or logically between the headend and subscriber. One example is an active double star architecture, with an intermediate hub site terminating an FM trunk and feeding AM video into fiber feeders out through the neighborhood. Depending on the need, the architecture can be configured for double-window (two wavelength) operation or single-window (one wavelength) operation. The second window would double the capacity for additional channels, provide on-line system diagnostics or some new interactive services that can be overlaid on the second wavelength.

For all distribution architectures, a pair of 1x2 tree couplers can be used to provide two-way transmission capacity over a bi-directional single fiber. One coupler is located in an optical network interface (ONI) module located at the front end of the link, and the other in an ONI module at the far end. The ONI executes the optical, opto-electronic and electronic functions necessary to interface with the coaxial cable plant for the drop into the home.

Additional subscriber services such as interactive home shopping or customized programming options can be supplied in the initial installation or phased in later as part of system upgrades. One method to add services and provide a partition between basic and enhanced services is to add optical channels by means of wavelength division multiplexing couplers. These couplers/splitters selectively channel most of the light power associated with a specific wavelength to the respective O/E (optical-to-electrical) interface. Such WDM couplers most likely would be located in the ONI at the headend and in an ONI near the subscriber premises.

Another active star design is a triple star architecture. In this design, fiber could be used between the headend and a pole or pedestal-mounted terminal, as described above.

Coax drops to the subscriber would deliver the basic entertainment services. Later, the architecture could evolve to fiber drops to subscriber premises through the use of 1xN tree couplers located in the pedestal (Fig. 8). This implementation, in essence, is a hybrid active/passive star architecture.

Passive Alternatives

A significant cost element in AM systems often is the linear AM laser transmitter. This must launch a high level of optical power, maintaining a linear relationship between the drive current and optical power. The tight performance specifications on these AM lasers results in a cost premium. Increasingly, 1x2, 1x4, or 1x8 couplers are being used to share or spread the cost of this transmitter between routes. AM cable television systems usually have a very limited loss budget, which places low-loss requirements on couplers and other system components. Another approach to optimizing the power balance among links in shared systems is to use variable ratio directional couplers, which are 1x2 couplers with an unequal power-splitting ratio. Wavelength division multiplexers also may be used in these systems to increase the number of channels per fiber or to enable on-line diagnostics. These couplers may be located either out in the cable plant or locally, nearer to the AM transmitter.

Table 2 lists the potential use of couplers by active, passive and cable TV backbone architectures.

IV. SYSTEM DESIGN TRADEOFFS

Implementation of coupler-intensive FBTT architectures must meet the system design goal of achieving the lowest installed cost per subscriber, while keeping open the technical potential for new revenue opportunities. These cost and design considerations being faced by system designers have a direct impact on the couplers required.

Multiple wavelengths can be used in FBTT systems to enable enhanced broadband services and an optical partitioning of the individual service levels. Multiple-window systems using WDMs also provide a means of cable plant sharing, conserving the fiber resource and helping to control costs. Furthermore, today's short-wavelength (~780 nm), CD-type lasers are lower in cost than their long-wavelength counterpart lasers. Use of short-wavelength CD-type lasers for low-bandwidth applications such as signaling and upstream communications provides a direct cost saving, but necessitates multiple-window system operation. Couplers must, in turn, meet system requirements for multiple-window operation.

V. COUPLER ENVIRONMENTAL REQUIREMENTS

The FBTT environment is characterized by harsh conditions, such as operating temperature extremes of -40°C to +85°C and humidity that reaches saturation levels. FBTT systems also face a variety of real-world intrusions such as flooding of leaky pedestals, exposure to unskilled personnel, or unintentionally left open ONI or pedestal doors, leading to exposure hardware to environmental extremes and animal and insect intrusion.

A number of tests have been established to evaluate the performance of couplers in the types of environments described above. The prospective user should insure that his or her coupler product has been fully tested for behaviour during exposure to the adverse conditions as well as after. This is essential because products in working systems must continue to function when the outside environment is hot, cold, or damp.

VI. COMPONENT CHALLENGES

The major significant challenge to fiber-optic component manufacturers, however, is the potential scale of FBTT deployment. There are hundreds of millions of potential subscribers around the world, so implementation of FBTT and telco subscriber loop activities will require production of passive components, optoelectronic components and systems in massive volumes. Manufacturing technologies must be optimized for high-volume production of high-performance components that exhibit the quality and reliability needed to take advantage of the enormous bandwidth of optical fiber and meet the projected long-life requirements of the coming systems. Moreover, the subscriber density leads to hardware space limitations, so require that systems and components must have small footprints to be accommodated in this high-density environment.

Thus, implementation of coupler-intensive FBTT architectures and the conditions under which these systems will operate impose severe system design constraints. These constraints, in turn, directly impact the requirements placed upon couplers.

As Table 3 illustrates, some single-mode architectures will place further demands on couplers, including wavelength independence (achromaticity); low insertion losses over a wide passband range; high isolation over wide passbands; short-wavelength operation; the ability to operate in multiple windows; and the ability to be fabricated in compact, monolithic structures. In addition, high-quality couplers will have to be manufactured in high volume, at low-cost. A number of vendors are developilng components that meet these challenges, and novel new technologies and devices are being introduced.

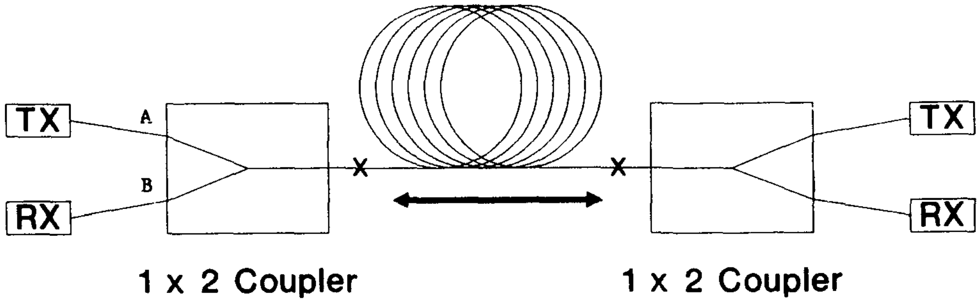

Figure 1. Use of couplers for bidirectional transmission over a single fiber.

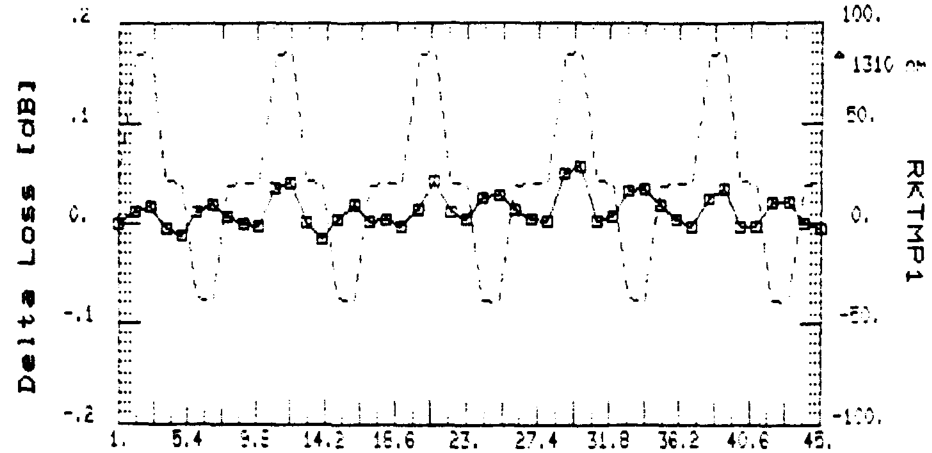

Figure 2. Change in insertion loss for a coupler port during temperature cycling.

Table 1. Coupler Specification Example for 1x2 50/50 Even Ratio Splitter and 90/10 Directional Coupler.

Element	Specification
Insertion Loss Over Optical Passband	3.8 dB for 50/50 Even Splitter 11.5 dB / 1.0 dB for 90/10 Dir. Coupler
Operating Temperature	-40°C to + 85°C
Maximum Insertion Loss Change over Temperature	± 0.2 dB
Change in Insertion Loss due to Polarization Effects	± 0.2 dB
Directivity	Better than 60 dB
Backscattering	Better than 55 dB
Tensile Strength on Fiber Pigtail	5 N
Tensile Strength on Tube/Cable	>10 N

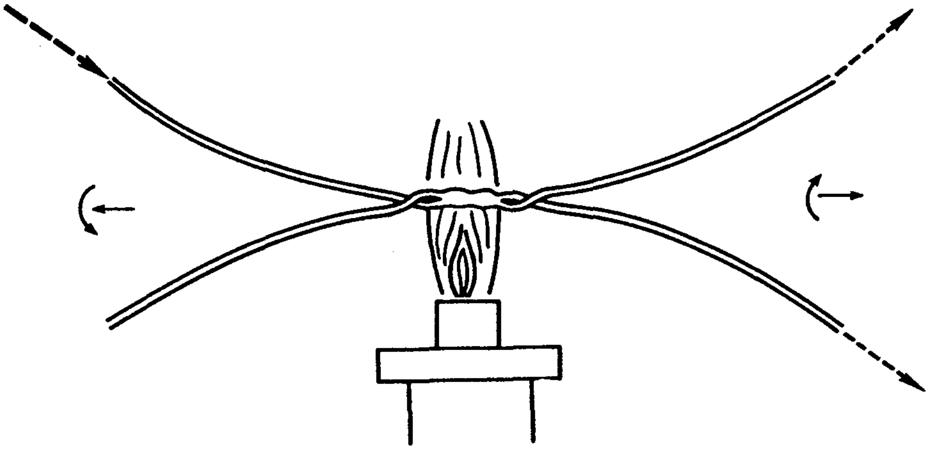

Figure 3. Fused biconic taper method of coupler fabrication.

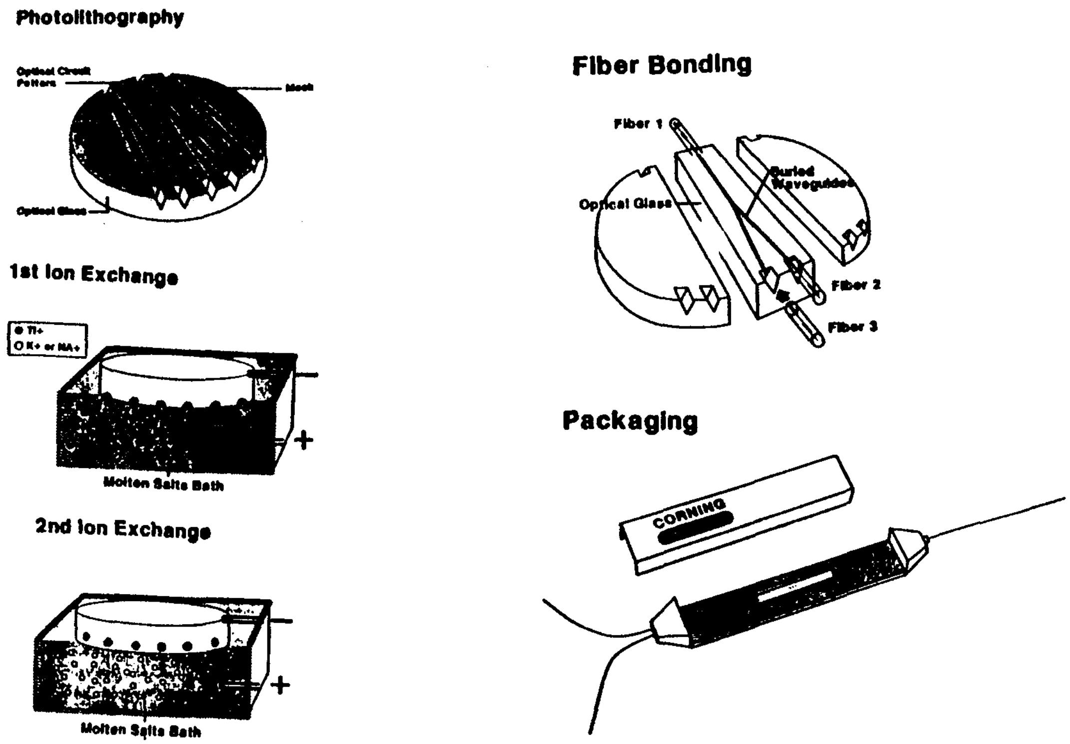

Figure 4. Coupler fabrication by Photolithography

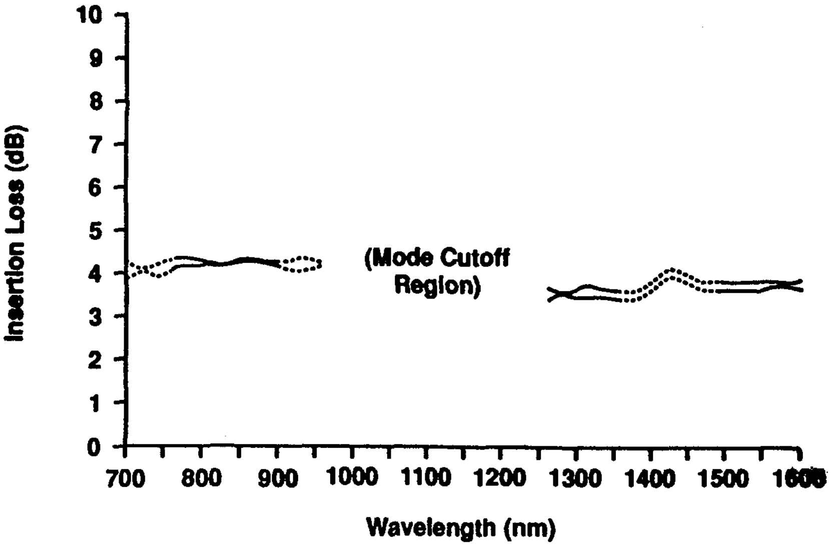

Figure 5. Insertion loss over wavelength for an achromatic coupler

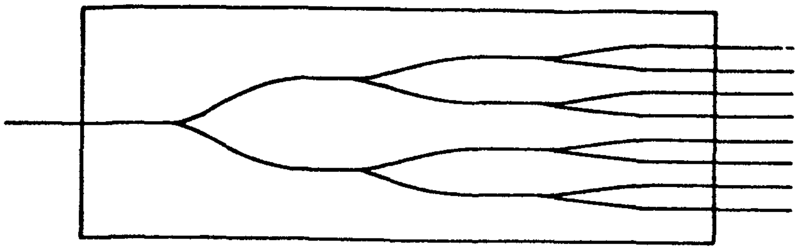

Figure 6. 1 x 8 Coupler made with passive integration of Y-Junction devices

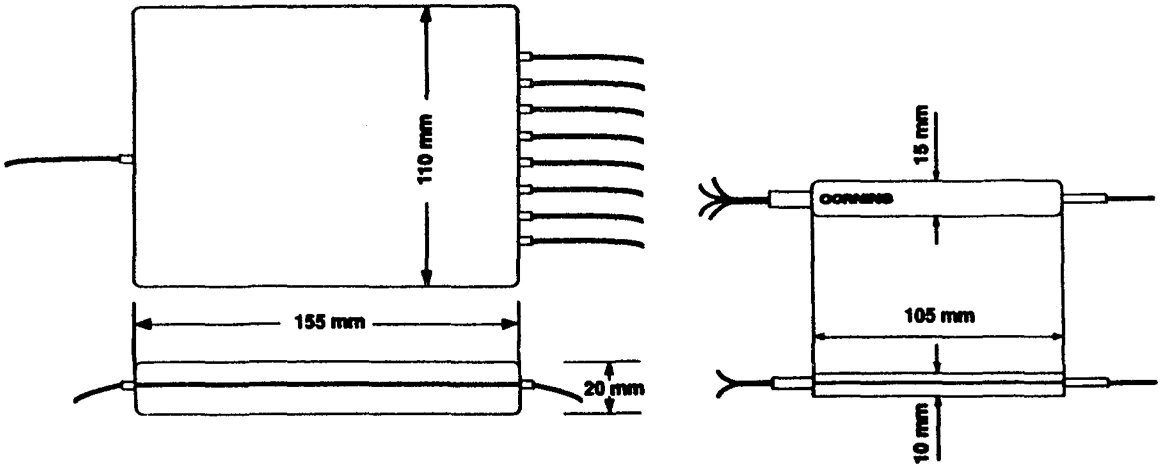

Figure 7. Comparison of size of FBT Cascaded 1 x 8 coupler and planar passive integrated Y-Junction coupler.

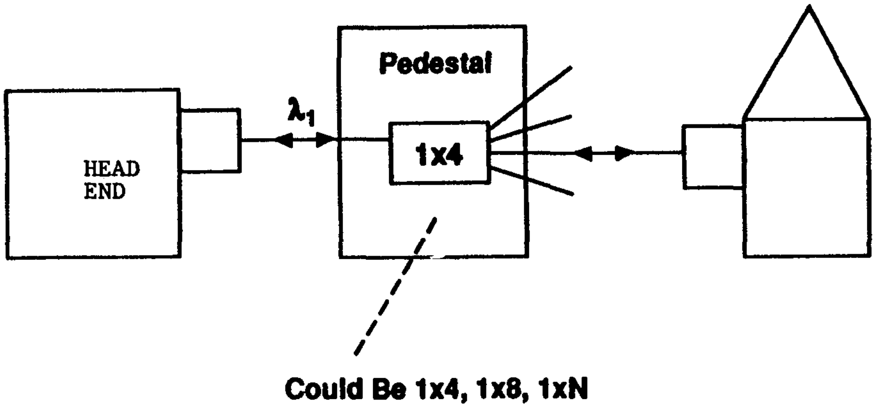

Figure 8. Pedestal network architecture example

Table 2. FTTS Architectures and Potential Coupler Uses

Architecture	Tap	1x2	WDM	1xN	2xN	NxM
Active Star		X	X			
Passive Star		X	X	X	X	X
Cable TV Backbone	X	X	X	X		

Table 3. FTTS System Design Constraints and Coupler Requirements

Implementations Requirements	System Constraints	Coupler
Uncooled lasers or LEDs, with wide source wavelengths.	Power budget over broad wavelengths.	Low uniformity and insertion loss over passband(s).
Low-launch power sources.		
Low-responsivity detectors.		
Low-dynamic-range detectors.		
Short wavelength sources.	Multiple window operation.	Achromaticity in all windows, low far-end crosstalk over passband.
Broadband avenue/upgrade.		
Optical service partition.		
Bi-directional transmission.	Reflections.	High directivity.
AM laser transmitter		Low backscatter.
Environment.	-40 to +85°C.	Mechanicals.
	Saturation humidity.	Packaging.
	Salt spray, other chemicals.	
	Real-world environment.	
Millions of subscribers.	High density, limited footprint.	Monolithic, compact structures, passive integration.
Millions of subscribers.	High volume.	Industrialization.
	Repetitive quality.	High reliability.
	Lifetime cost.	
	Installed cost.	