TUTORIAL

Gigabit Communications over Plastic Optical Fiber

Opportunities and challenges for the home network.

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Plastic optical fiber (POF) is a fiber technology developed decades ago to provide low-data-rate communications with easy handling and high immunity to electromagnetic interference. Traditional fiber technologies such as single-mode fiber (SMF) and multimode fiber (MMF) use 10–62.5-μm glass or silica fiber cores for light transmission, while POF utilizes 1-mm plastic cores [1]. A typical POF link is shown in Figure 1, where the optical and electrical domains have been labeled separately.

A classic POF data link consists of three parts:

1) a transmitter, consisting of a driver, a light source such as a light-emitting diode (LED) that converts electrical signals into optical pulses, and a lens that helps to couple the light into the POF
2) a communication channel, realized by a polymethylmethacrylate (PMMA)-based POF cable
3) a receiver, consisting of a photodetector (PD) that converts incoming optical pulses into electrical signals and a receiver that further processes the electrical signals (a lens similar to that used in the transmitter may be added at the receiver to help couple light from the POF into the PD, but the lens can be skipped when the sensitive area of the PD is similar in size to the POF core).

POF systems have been used extensively in automatic control equipment in rugged manufacturing environments, under industrial standards such as PROFIBUS, SERCOS, and INTERBUS-S [2], [3]. In consumer data communications, the first widely used standard is TOSLINK, released by Toshiba for Sony-Philips-Digital-InterFace (S/PDIF), which is used for high-quality digital audio transmission [4]. Another sector that has used POF systems widely is the automotive industry, where POF systems have been adopted for information and multimedia transmission inside vehicles. The first industrial standard for POF from the automotive industry was the Digital Domestic Bus (D^2B), released in 1998 by Daimler-Benz, which used a 1-mm

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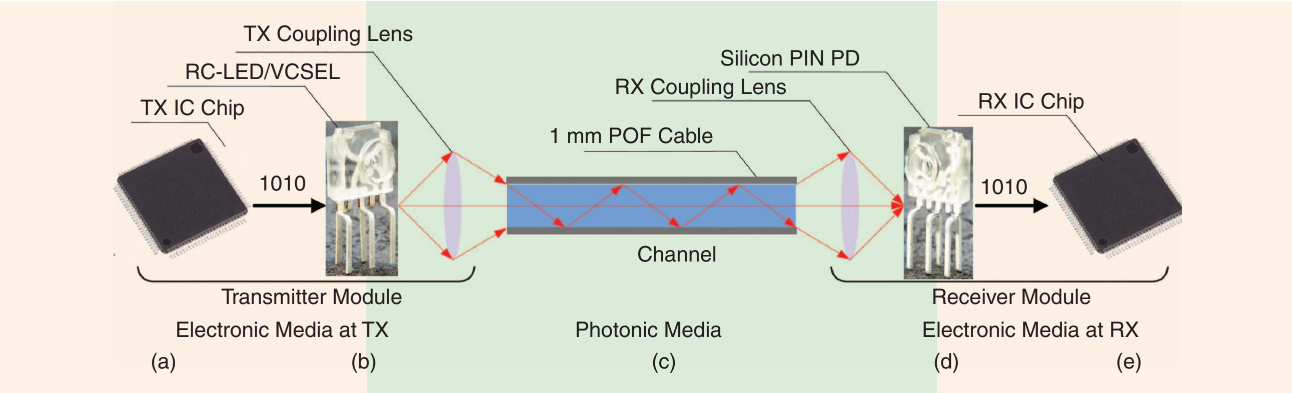

FIGURE 1: A typical POF link consists of (a) a transmitter chip, (b) a light emitter with coupling lens, (c) a POF cable, (d) a light detector with a coupling lens, and (e) a receiver chip.

POF link routed as a duplex signal bus ring at a data rate of 5.6 Mb/s. In 2001, D^2B evolved into the Media-Oriented Systems Transport standard, with a maximum data rate increased to approximately 150 Mb/s [3]. Meanwhile, BMW introduced another standard, called "byteflight bus," which focuses more on reliability; the data rate is around 10–50 Mb/s. An important commercialization step in POF technology was the introduction of IDB-1394, a combination of the IEEE 1394b and Intelligent Transportation System Data Bus standards [3]. IDB-1394 is designed to provide a higher data rate of 250 Mb/s for automotive as well as household Fast Ethernet applications through the use of step-index POF (SI-POF) with fibers as long as 20–30 m [3].

Figure 2 summarizes most of the commercial POF transceivers currently available on the market. These transceivers utilize LEDs for their light sources, except for one released by Toshiba in 2003, which uses a red laser diode to provide a higher data rate of around 625 Mb/s. Firecomms recently reported a state-of-the-art POF transceiver that supports a 1.25 Gb/s data rate over 10-m SI-POF, with a red vertical-cavity surface-emitting laser (VCSEL) [5] utilized in its transmitter.

Gigabit Home Network: Coaxial Cable, Traditional Fiber, or POF?

Since Alexander Graham Bell invented the telephone in the 1870s, the routing of electronic signals in the home has become increasingly prevalent. Today, typical houses in North America are crowded with many electrical wire connections, such as phone lines, coaxial TV cables, and twisted-pair Ethernet cables, all of which are illustrated in Figure 3. The trickiest wiring problem is posed by rigid coaxial cables. A typical coaxial cable contains a metal core and a metal shielding layer separated by a polymer insulator dielectric; all of these are covered by a plastic jacket. A comparison of a commonly used RG-6 TV coaxial cable with 1-mm POF cable is given in Figure 4. In this case, the jacketed POF cable is four times smaller in diameter (16 times smaller in cross-sectional area) than a typical coaxial cable.

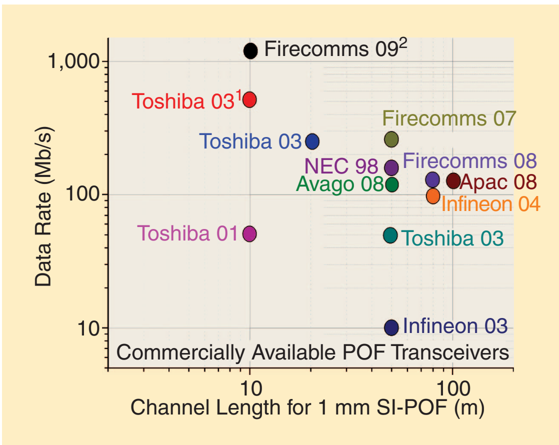

FIGURE 2: State-of-the-art, commercially available POF transceivers from various suppliers. The POF transceivers shown above use LEDs as light emitters except for (1), which utilizes a red edge-emitting laser diode and (2), which utilizes a red VCSEL.

Nowadays, the demand for high-speed data communication in the home at rates of multiple gigabits per second is rapidly increasing in response to the desire to send high-definition, uncompressed video around the home. For 1080/60p streaming high-definition television (HDTV) signaling, a raw data rate of 2.97 Gb/s per channel is required [6]. Coaxial cable systems encounter difficulties in adapting to such high data rates for longer channel lengths. In addition, installing coaxial cables in a preexisting house requires trained professional personnel with proper cutters and termination tools.

As an alternative, a POF system potentially provides a higher data rate for longer channel lengths and is considerably easier to install. For example, POF fiber can easily be hidden under painted tape. A second advantage is a POF system's provision of better immunity to noisy electromagnetic interference from home appliances and parallel channels. POF cable is also more secure than coaxial cable against undesired surveillance due to its optical nature. POF cable should be cheaper to purchase in the future in high volumes because of its polymer material. The most attractive benefit of the use of POF as a replacement for coaxial cable arises from its easy "cut-and-plug" termination, shown in Figure 5

> **A classic POF data link consists of three parts: a transmitter, consisting of a driver, a light source, a communication channel, and a receiver.**

with an OptoLock connector [7]. No fancy tools or professional "geek" skills are needed to make a good POF termination. Different POF connectors are available from various vendors; some alternative examples are shown in Figure 6. There are also other benefits to the use of POF as a replacement for coaxial cables, such as the decoupling of electric voltage levels at the transmitter and the receiver, which provides the freedom to hook up various electronic devices with different voltage levels and eliminates the noise loop through the common ground. Table 1 summarizes the many significant advantages of POF systems.

Alternatives to POF include the traditional SMF and MMF glass fibers. These can provide transmission rates of greater than 10Gb/s, with channel lengths as long as 1 km (and even longer, such as inter-metro systems)—a performance that is superior to that of both coaxial cable systems and POF systems. But the superior performance of these two fibers arises from tiny glass/silica cores with delicate connectors, a makeup that imposes tight alignment requirements during termination and installation. A typical comparison of SMF, MMF, and POF cable cross-sectional views is provided in Figure 7 (not drawn to scale). In summary, SMF and MMF systems are difficult to handle, and the installation costs are prohibitively high for most home owners.

Why is POF not currently being used at multigigabit data rates? The contention here is that all significant limitations to the extension of POF data rates to multiple gigabits per second have recently been—or can be—circumvented.

As previously stated, commercial POF systems usually support data rates of up to 250 Mb/s at a channel length of 50–80 m. Typical POF cables have a uniform core material with an identical refractive index, coated by a cladding material with a lower refractive index in order to confine the light within the fiber core. The uniform refractive index is the source of the term *step-index POF.* Due to the large dimension of the core, multimode transmission occurs along the POF; in fact, more than 30,000 modes exist inside a 1-mm SI-POF core. A uniform core refractive index results in a uniform ray transmission velocity, which causes different travel times for the various modes. This different time delay, also called the *differential*

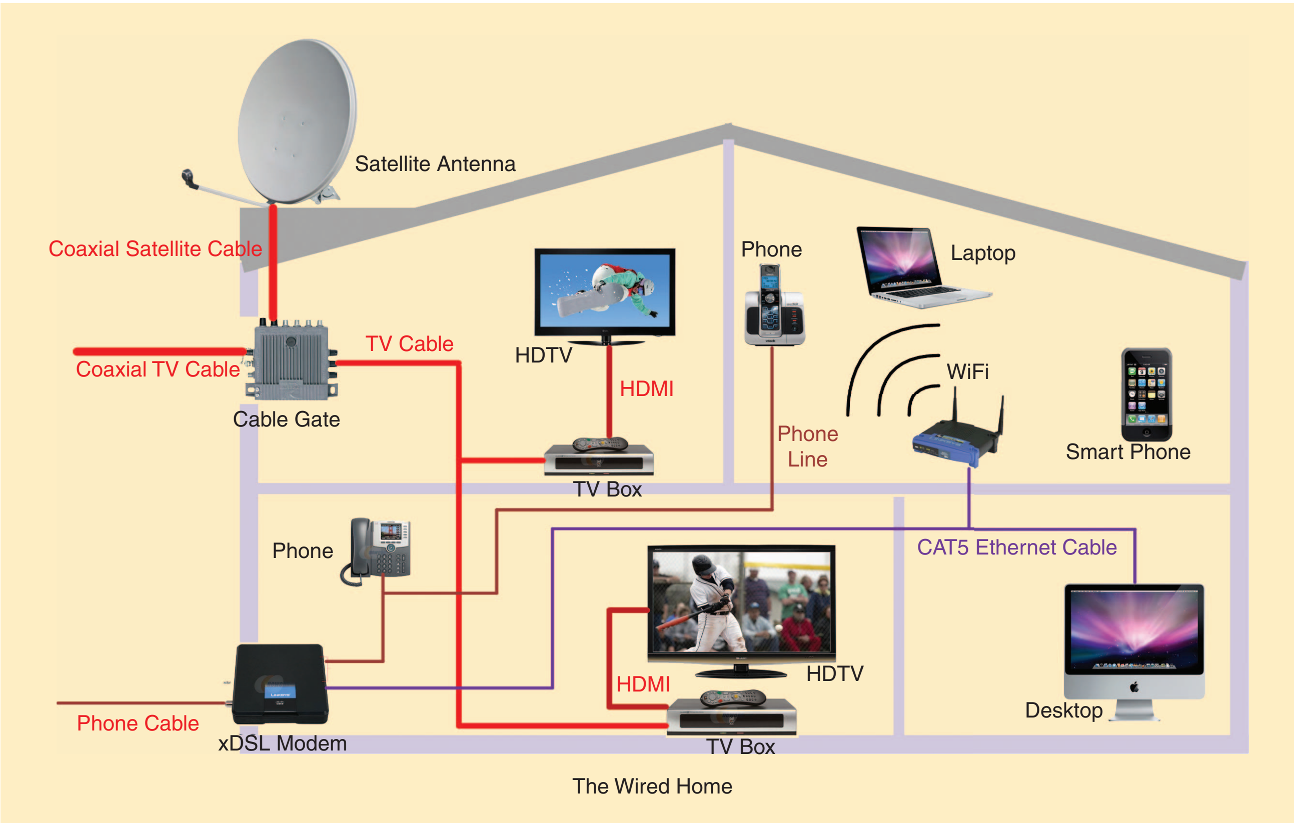

FIGURE 3: A house wired with regular coaxial cables and twisted-pair cables.

time delay (DTD), causes a narrow light pulse at the POF input to become a more widely dispersed pulse at the POF output. A simulated pulse broadening via a 50-m SI-POF is shown in Figure 8. This phenomenon is known as *multimode dispersion*. This dispersion is more severe in POF, due to its large core size as compared with MMF and especially as compared with SMF. The DTD among different modes increases as the POF's length is increased; this process results in an approximately constant product of bandwidth and channel length. A typical value is 5 MHz·km:

$$\text{Bandwidth(MHz)} \approx \frac{5000\ \text{MHz}\cdot\text{m}}{\underset{\text{(meters)}}{\text{Channel Length}}}.$$

This relationship between the POF bandwidth and the channel length explains the current performance limitations of POF transceivers that have nonequalized receivers. For graded-index POF (discussed later in this article), the proportionality constant is much larger, on the order of 150 MHz·km.

Assuming that a higher-speed light source is available at the transmitter, higher-speed SI-POF systems are possible at shorter channel lengths. As shown in Figure 2, the highest data rate for POF transceivers with LED transmitters is around 250 Mb/s, while 1.25 Gb/s is achieved by using a red VCSEL at a channel length of 10 m. The reasons why most current commercial POF transceivers do not use high-speed red lasers are threefold:

1) A high-speed red laser diode is more expensive than a red LED.
2) Most applications did not historically require a gigabit data rate, and a rate of 100–250 Mb/s was considered sufficient for automobiles and industrial control applications.
3) The constraints of other link components, such as the dispersive behavior of the SI-POF channel and the speed of the receiver module, limited the speed even when a fast laser was utilized.

As an alternative, a POF system potentially provides a higher data rate for longer channel lengths and is considerably easier to install.

All of these factors contribute to the current status of POF transceivers, which function at around 100–250 Mb/s at channel lengths of 50–80 m.

The last bottleneck impeding high data rates in a POF link is at the receiver's front end, which typically consists of a photodetector and a receiver circuit. Commercial products usually use external silicon PIN diodes (a PIN photodiode is similar to a regular PN photodiode, except that the PIN photodiode has an intrinsic layer between the P-type and N-type doped regions) as photodetectors because their thick intrinsic regions

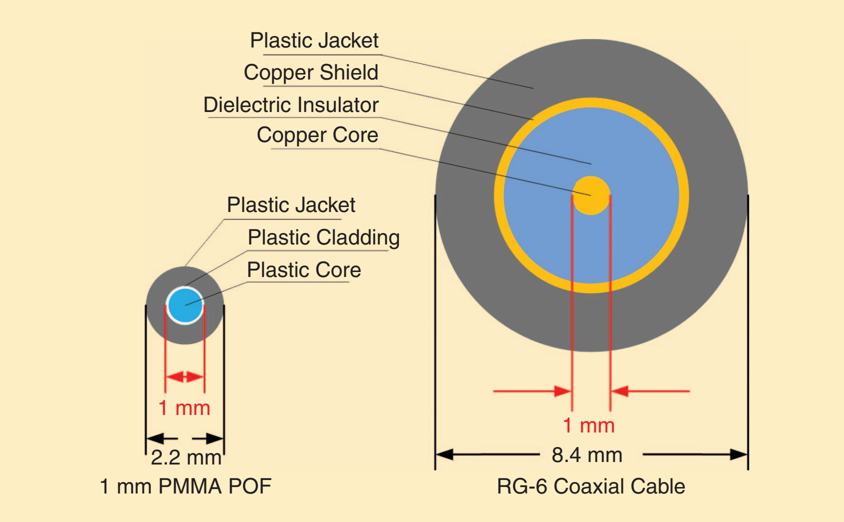

FIGURE 4: Cross-sectional comparison between a 1-mm POF cable and an RG-6 coaxial cable.

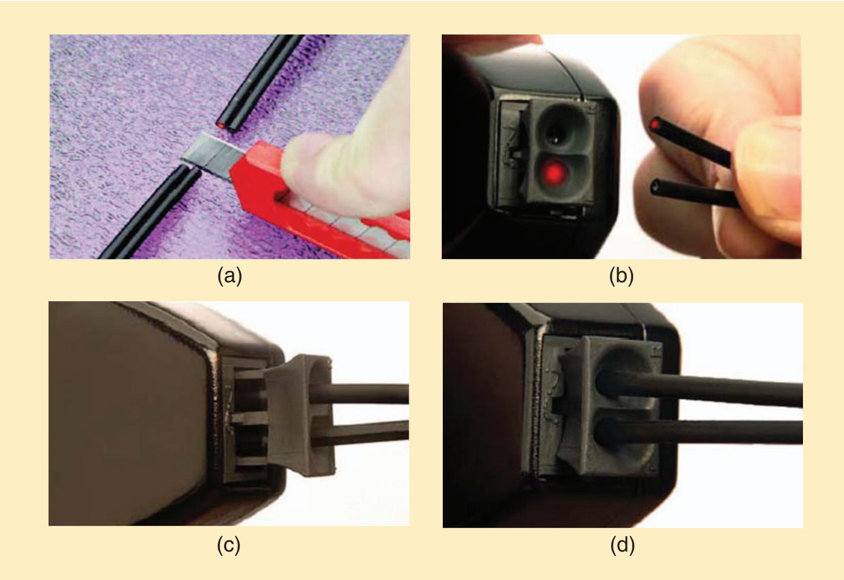

FIGURE 5: Simple "cut-and-plug" termination of a large-core duplex POF cable with an OptoLock connector [7]. (a) Step 1, slice the POF cable with a knife. (b) Step 2, split the POF strands. (c) Step 3, insert POF cable into OptoLock Connector. (d) Step 4, press Optolock to hold POF cable steady.

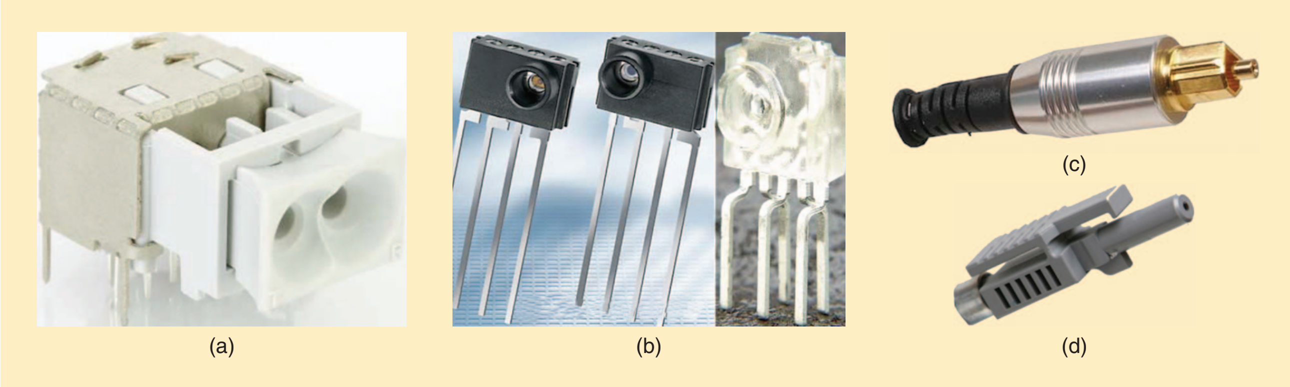

FIGURE 6: Various simplex and duplex connectors for terminating large-core POF cables: (a) OptoLock duplex connector from Firecomms; (b) cavity-as-interface (CAI) connector for the automotive industry; (c) TOSLINK simplex connector for S/PDIF; (d) Avago simplex connector from Avago.

can be fully saturated for fast and efficient photon absorption. (A lower intrinsic doping level plus a higher reverse bias voltage create a deeper depletion region in which carriers are created by the incident photons; the carriers drift with high velocity to the terminals.) However, PIN and PN photodiodes have intrinsic parasitic capacitance, denoted by C_{PD}, which is proportional to their active areas. Other electrical parasitics, such as

TABLE 1. COMPARISONS AMONG RG-6 COAXIAL CABLE, SMF, MMF, SI-POF, AND GI-POF.

PARAMETERS	RG6 CABLE	SMF	MMF	SI-POF	GI-POF
Core material	Copper	Glass	Glass	PMMA	PMMA
Ground layer	Yes	No	No	No	No
Core diameter	1 mm	0.01 mm	0.05 mm	0.98 mm	0.9 mm
Cladding diameter	NA	0.125 mm	0.125 mm	1 mm	1 mm
Jacket diameter	8.4 mm	2.5 mm	2.5 mm	2.2 mm	2.2 mm
Weight	40 g/m	5.1 g/m	5.1 g/m	4.0 g/m	4.0 g/m
Min bending radius	$>$ 20 cm	5 cm	5 cm	2.5 cm	2.5 cm
Signal type	Electrical	Optic	Optic	Optic	Optic
Signal wavelength	NA	1.55 μm	0.85 μm	0.65 μm	0.65 μm
Numeric aperture	NA	$<$ 0.13	$<$ 0.2	0.5	0.35
DC attenuation	$<$ 1 dB/km	$<$ 1 dB/km	3 dB/km	165 dB/km	165 dB/km
Bandwidth[1]	7 Mhz/km	$>$ 5 Ghz/km	$>$ 1 Ghz/km	5 Mhz/km	150 Mhz/km
Modal dispersion	NA	NA	Weak	Strong	Weak
Lens at TX	No	Yes	Yes	Yes	Yes
Lens at RX	No	No	No	Yes[2]	Yes
Special connector RX	Coax BNC	Yes	Yes	No	No
EMI sensitivity	Yes	No	No	No	No
Ground loop	Yes	No	No	No	No
Security versus tapping	Low	High	High	High	High
Cross talk	Yes	No	No	No	No
Special cutter	Yes	Yes	Yes	No	No
Volume material cost	High	Medium	Medium	Low	Low
Connector cost	Low	High	High	Low	Low
Jacketed cable cost[2]	1.0 USD/m	0.4 USD/m	0.3 USD/m	0.5 USD/m	1.0 USD/m

[1]The bandwidths are measured as −3 dB cutoff frequencies.
[2]The costs quoted for POF cables are for a limited volume.

bond-wire inductance between the PIN PD and the receiver's integrated circuit, form a low-pass filter with the detector capacitance, which attenuates high-frequency signals generated by the PIN PD. This filtering effect is less important for applications below a few hundred Mb/s; the effect can be significant for multigigabit applications, however. Designers may select PIN PDs with smaller dimensions in order to reduce C_{PD} and therefore minimize attenuation caused by the bond-wire inductance. This alternative requires a more critical receiver lens to collimate the light from the POF onto the PIN PD. A PIN PD with a dimension of 50 μm requires a folding ratio of 20, which imposes a tight alignment tolerance during fabrication. Such a requirement makes system integration more complex and increases production costs.

Speed limitations caused by the receiver circuits are currently being minimized. A typical POF receiver front end consists of a transimpedance amplifier (TIA), a post-amplifier (PA), and a clock/data recovery circuit. The first challenge is to realize a TIA with an input impedance low enough to minimize speed limitations caused by the large parasitic capacitance of the PD. In addition, SI-POF cables exhibit dc attenuation, which is approximately 165 dB/km at around 650-nm wavelength [1]. This translates to around 8 dB attenuation for a 50-m POF link. Therefore, the available signal power at the receiver input will be relatively low, and a sensitive low-noise receiver preamp is necessary for reliable communications. In sum, a receiver front end capable of driving a large C_{PD} at data rates of a few Gb/s while exhibiting a high optical sensitivity is desired. Table 2 illustrates a typical link budget for a commercial POF system.

Opportunities and Challenges for Gigabit POF

It is now possible to extend the data rates of POF systems by almost an order of magnitude by taking

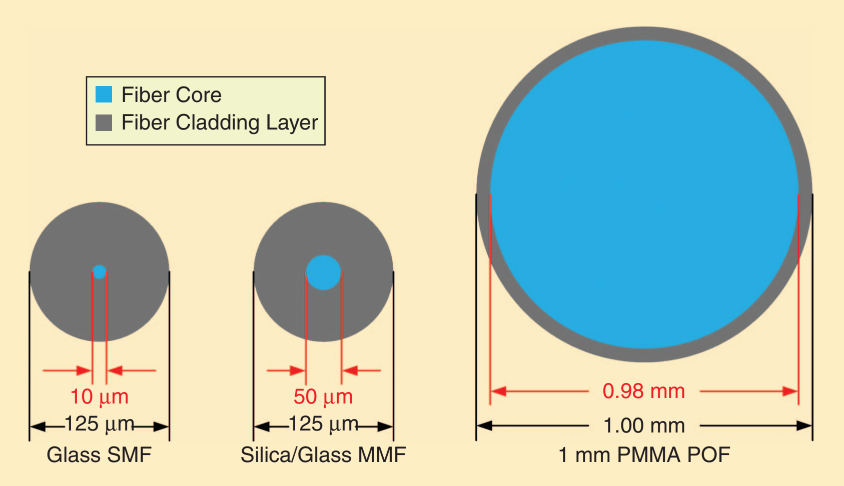

FIGURE 7: Cross-sectional comparisons of typical SMF, MMF, and POF cables without jackets (not drawn to scale).

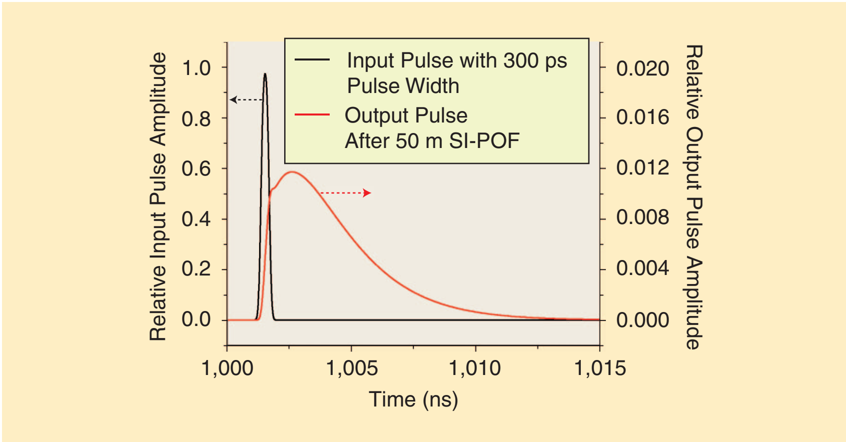

FIGURE 8: Pulse broadening through a 50-m SI-POF channel.

TABLE 2. TYPICAL LINK PLANNING FOR LARGE-CORE POF SYSTEMS.

COMPONENT	POWER/LOSS	NOTE
	Typical	
Optical output power from VCSEL	2 dBm	Red VCSEL from OptoWell
Temp variation's effect on laser	1 dB	On a red VCSEL
VCSEL power distribution	1 dB	On a red VCSEL
Coupling loss from VCSEL into POF	3 dB	Simple lens or bare coupling
Additional loss in first few meters	1 dB	Due to excessive modes attenuated
Attenuation 30 m 1 mm PMMA POF	5 dB	165 dB/km for 1 mm PMMA POF
Coupling loss from POF onto PD	3 dB	Simple lens or bare coupling
Aging effects on components	1 dB	Most accounted for emitter and lens
Bending losses	0.5 dB	5 bendings with radius > 3 cm
Link margin	2 dB	Including margin for RX and channel
Available optical power onto PD	− 15.5 dBm	

> **The most important advance was perhaps the development of high-speed red VCSELs by companies such as Firecomms.**

advantage of recent breakthroughs and advances. These have taken place in the optoelectronic components, in the system-level packaging techniques, and in receiver circuit designs.

The most important advance was perhaps the development of high-speed red VCSELs by companies such as Firecomms [5]. Today, red VCSELs are commercially available from multiple vendors. These include 670-nm VCSELs from Firecomms and Optowell. The current general belief is that several fabrication difficulties prohibiting commercial usage of red VCSELs have now been solved [5]. As a laser diode sandwiched between two distributed Bragg reflectors, a VCSEL offers a higher speed while maintaining a relatively narrow output spectrum width, denoted *full width at half maximum* (FWHM) width. As shown in Figure 9, a wide FWHM means that the emitted optical power is distributed over different wavelengths; this distribution produces chromatic dispersion along a fiber channel due to the different ray transmission speeds at different wavelengths. The red VCSEL from Firecomms has a cutoff frequency higher than 3 GHz [5] and a FWHM of less than 1 nm, both of which are almost 20 times better than competing LEDs. The distributed Bragg reflector structures also help to increase the electrical-to-optical conversion efficiency. As a result, red VCSELs can emit higher optical power than LEDs. A comparison of VCSELs with traditional high-speed red edge-emitting laser diodes indicates that VCSELs have the advantage of being vertical devices. This characteristic makes their volume manufacturing and testing easier and less expensive. To sum up: with the use of red VCSELs, the speed bottleneck at the transmitter is significantly relaxed while the available optical power from the transmitter is simultaneously increased.

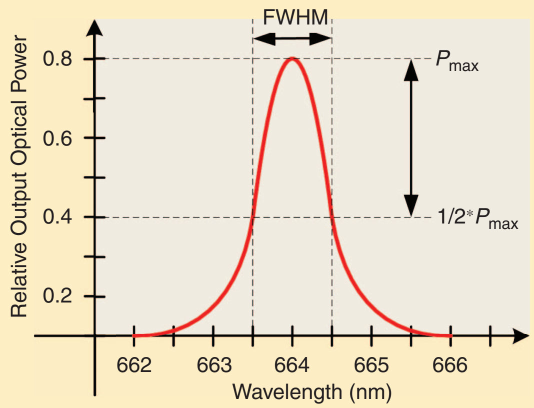

FIGURE 9: Graphical definition of FWHM for an optical emitter.

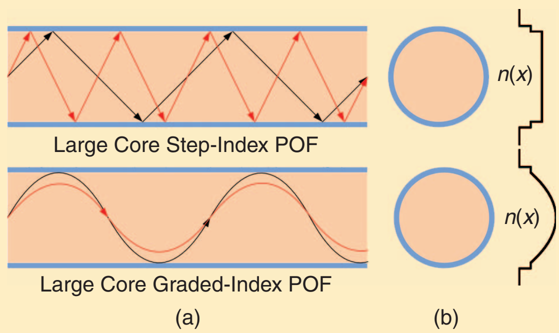

FIGURE 10: Comparison of (a) ray transmissions and (b) refractive index distributions in SI-POF and GI-POF.

For decades, researchers have been investigating graded-index POF (GI-POF). GI-POF is made of material (PMMA) identical to that used in SI-POF, but its refractive index varies from the center to the outer edge of the fiber [8]. Figure 10 contrasts ray transmission inside SI-POF and inside GI-POF. Instead of the uniform core refractive index $n(x)$ found in SI-POF, GI-POF has a curved distribution of refractive index $n(x)$ decreasing from its core center toward its core edge. This increases the ray transmission speed closer to the core edge, an increase that compensates for the longer traveling distances of higher modes. As a result, GI-POF exhibits much less multimode dispersion as compared with SI-POF of the same size. A typical 50-m, 1-mm PMMA GI-POF provides a bandwidth of around 3 GHz, which is 30 times greater than that of a PMMA SI-POF [9]. A minor disadvantage of GI-POF is its reduced numerical aperture (0.3–0.4), which is slightly less than that of SI-POF (0.5). This difference causes a slightly reduced acceptable input light-coupling angle but does not affect most of the benefits of using large-core POF systems. With 1-mm GI-POF, the bandwidth of the POF channel has been greatly boosted with only a modest increase in the fabrication cost; the current cost of 1-mm GI-POF (calculated on the basis of small volumes) is US$1 per meter, as compared with $0.50 per meter for 1-mm SI-POF. Since they share the same material, their volume costs should decrease and converge as volumes grow higher.

Newer technologies have recently improved the speed at the transmitter and the channel; the current bottleneck that impedes speed occurs due to the receiver bandwidth. Some relatively fast silicon PIN photodetectors have been reported during the past few years. These higher speeds were attained by reducing their active areas and therefore their parasitic capacitances. Today, these silicon PIN diodes can achieve cutoff frequencies of 1–2 GHz. Although bandwidth limitations that occur because of the detector capacitances can be minimized by using a low-input impedance preamp, there are still bandwidth limitations that occur because of the bonding-wire inductance. These inductances are especially problematic for POF systems (as compared with glass fiber systems) due to the large detectors commonly used. A possible way to minimize inductor limitations is to use system-in-a-package (SIP), where bond-wire lengths are minimized.

Another way to minimize bond-wire inductance limitations, assuming a SIP package, is to use a custom PIN PD similar to that shown in Figure 11. Without going into the details, this differential approach may be described as one that uses a "dummy" detector to minimize the effects of the cathode inductance. The anode inductances are kept very short in this approach, and, therefore, their bandwidth limitations are also minimized. Indeed, when mutual coupling is taken into account, an effective differential inductance as small as 500 pH each is possible.

An alternative to the use of an external PD is the integration of the PD on the receiver die. This integrated PD ideally utilizes preexisting diode structures in CMOS and BiCMOS

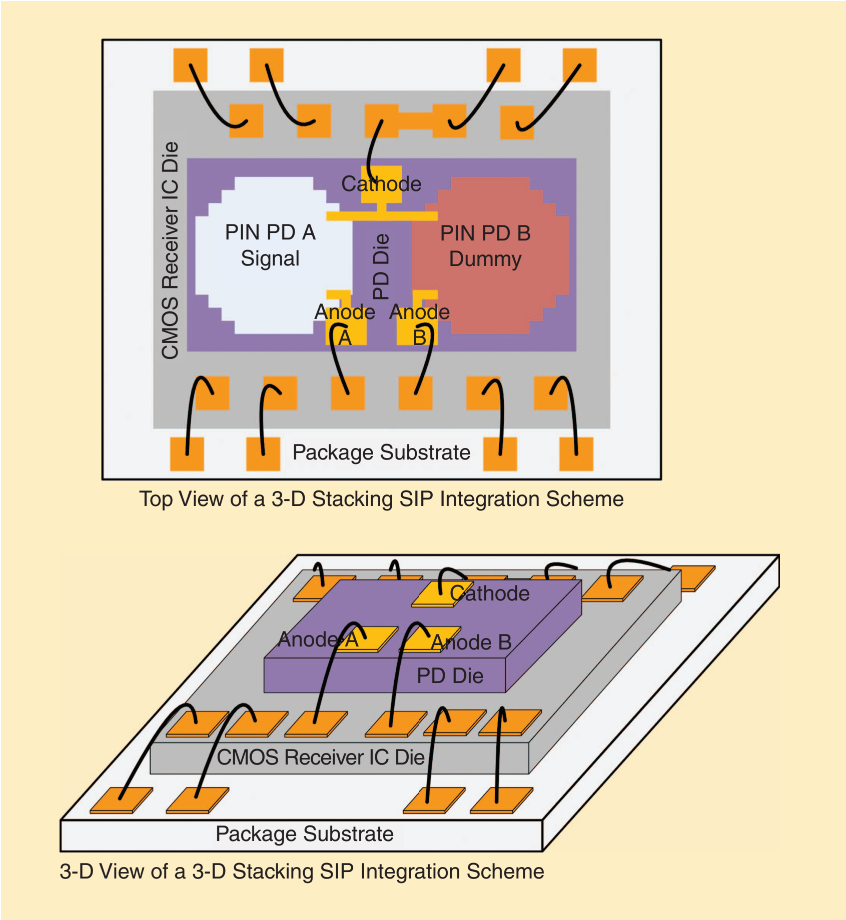

FIGURE 11: Stacked SIP integration with a customized PIN PD die and a receiver chip. The two anode pads (anode A and anode B) will be wire-bonded onto two chip pads, which are the differential inputs of the receiver. The shared cathode pad is a differential ac ground, and it will be wire-bonded onto a package lead.

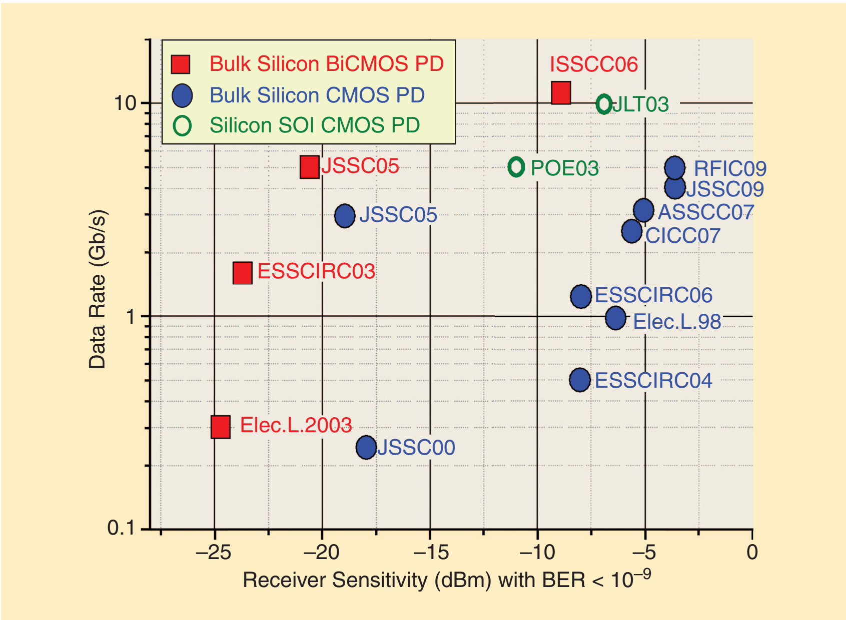

FIGURE 12: State-of-the-art integrated PDs in CMOS, SOI CMOS, and BiCMOS processes.

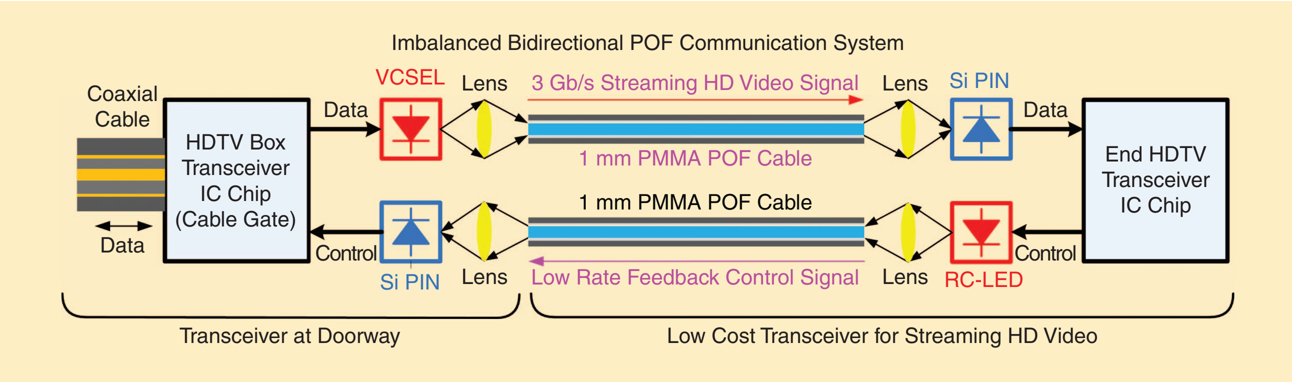

FIGURE 13: An imbalanced bidirectional POF link for streaming uncompressed HDTV signals. The HDTV box uses a red VCSEL to transmit uncompressed HD video signals to the TV, while an LED at the TV transmits back the low-data-rate control signals.

ACRONYMS

CDR	Clock and data recovery
D²B	Domestic digital bus
DBR	Distributed Bragg reflector
DDC	Display data channel
DTD	Differential time delay
FWHM	Full width at half maximum
GI-POF	Graded-index plastic optical fiber
IC	Integrated circuit
IDB	Intelligent transportation system data bus
LED	Light-emitting diode
MMF	Multimode fiber
PA	Post-amplifier
PD	Photodetector
PMMA	Polymethylmethacrylate
POF	Plastic optical fiber
PROFIBUS	Process Field Bus (standard)
RX	Receiver
SERCOS	Serial Real-Time Communication System (standard)
SIP	System-in-a-package
SI-POF	Step-index plastic optical fiber
SMF	Single-mode fiber
SML	Spatial modulation
TIA	Transimpedance amplifier
TOSLINK	Toshiba-Link (proprietary system)
TX	Transmitter
VCSEL	Vertical-cavity surface-emitting laser

processes. The benefits of an integrated PD include higher system-level integration, lower cost, and the elimination of the interface bond wires. An integrated PD (in a CMOS process) exhibits a slow response due to its shallow depletion region, however. This occurs due to the highly doped substrate and limited supply voltage found in a submicron CMOS process. The speed of an integrated PD can be improved by blocking the electron diffusion component that is relatively slow; this blocking can be accomplished by adding physical blocking layers, as in the silicon-on-insulator (SOI) CMOS process [11] or by using differential slow-carrier subtraction techniques known as spatial modulation (SML) [12]. These techniques trade off optical sensitivity in order to increase speed. The resulting sensitivities are inadequate for POF links with channel lengths greater than 30–50 m. Alternatively, linear analog equalization (EQ) can be added after the TIA to compensate for the slow response of a CMOS PD, without a requirement for any SML techniques [13]. Ideally, in order to obtain a good PD responsiveness with high speed, a lightly doped region of a depth greater than 5 μm and a relatively high reverse bias voltage are desired; these are usually available only in BiCMOS or old CMOS processes. The current state-of-the-art integrated PDs are summarized in Figure 12. PDs in CMOS and SOI CMOS processes can achieve data rates of up to 5 Gb/s at the cost of receiver sensitivities, while PDs in BiCMOS processes are generally faster and more sensitive [14].

Since fiber-optic communication systems necessarily require significant digital signal processing, cost reductions occur when the POF receivers can be included along with the digital systems in a modern submicron CMOS process, such as a 65-nm or even a 45-nm CMOS process. POF receivers in submicron technologies have slower responses.

The slowness occurs because a larger portion of the detector current is conducted by slowly moving carriers in the substrate, rather than by fast carriers in the depletion region. In addition, the detector capacitances are larger due to higher doping levels. The detector capacitance for a 500 μm by 500 μm octagonal n-well/p-substrate PN photodiode in a typical 65-nm CMOS process is more than 40 pF, which is prohibitively large for multigigabit applications. Typical BiCMOS technologies can realize photodetectors with larger depletion regions, which are superior for POF applications to those in submicron CMOS technologies. This superiority constitutes a strong argument for a two-chip, BiCMOS/CMOS receiver solution for applications requiring longer link lengths.

To summarize, three approaches are possible: a nonintegrated PD in a SIP package; a two-chip BiCMOS/CMOS solution, possibly in a SIP package; and a single-chip solution in a deep submicron CMOS process, probably with a lens included in its package and short link lengths. The preferred approach depends on the required speed and channel lengths and primarily involves a trade-off of cost versus performance.

System Considerations for Streaming HDTV in the Home

Streaming uncompressed HDTV signals in the home generally requires data rates of 2.97 Gb/s and cable lengths of 30–50 m. In addition, most HDTV displays need to transmit some control signals back to the HDTV gate, such as display data channel (DDC) signals. The typical data rates of back-channel control signals are below tens of Mb/s. This practical usage for streaming HDTV creates an unbalanced data rate duplex channel between the HDTV gate and the HDTV display. As shown in Figure 13, a high-speed red VCSEL transmitter at the HDTV gate is preferred for sending the 3-Gb/s downstream video signals; a less expensive LED transmitter can be used at the display end for sending the DDC signals. If a blue or green LED can possibly be used at the HDTV display, then perhaps a simplex POF channel with wavelength division multiplexing (WDM) could be used to replace the duplex POF channel. Such POF transceivers would be truly low-cost and easily installed systems.

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