*White Paper*

# Causes of Return Loss at Mated Single Mode Fiber Optic Connections

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*September 2021*

## Abstract

Return loss in fiber optic connections can significantly degrade system performance. Connections will exhibit return loss even if they are perfectly clean and possess ideal geometries. This paper explains how the complexities of different physical connections contribute to return loss . Contributions from small refractive index differences between fibers, damage caused by endface polishing, and fiber deformation due to the connector spring force are explored. This paper also explains how an angle polished on the fiber and connector helps to significantly reduce the return loss by directing reflected light at the endface of the connector out of the fiber core, hence reducing the light traveling back towards the source.

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# Exploring Causes of Return Loss at Mated Pairs

Low return loss is critical in ensuring operability of fiber optic communication systems. As transmission rates increase and more complicated communication schemes are implemented, such as PAM4, any return loss becomes a strong concern. Return loss is the result of back reflections, and excessive back reflections can induce noise on the signal leading to increased data transmission errors. There are many sources of return loss in a fiber optic system. This paper will analyze sources of return loss that are still present when perfectly clean and ideally shaped fibers are mated together.

**Note:** The term Optical Return Loss typically describes total return loss across a cable assembly or a link. The term Reflectance describes a single reflection in an optical assembly. Reflectance occurs at point discontinuities, for example connector interfaces, splice interfaces, etc. Typically, Return Loss is reported as a positive number and Reflectance is a negative number. The industry commonly uses the term Optical Return Loss when related to connectors and mated connections. This document uses Return Loss to describe the ratio of reflected light at mated connectors and uses a negative sign convention.

## Connection Return Loss

When assembling fiber optic cables, typically the connectorized ends are verified for acceptable return loss levels. The connectorized ends of a patch cord will be mated to other connectorized cables in a fiber optic system, which results in a reflection at the mated pair of connectors. This mating of two connectors is termed a “connection.” When two connectors are mated, the performance of the connection is a result of the quality of each connector. During the measurement process it is the connection (mating of two connectors) that is qualified.

## Fresnel Reflections

In general, reflections in optical systems occur when light passes from one medium to another medium with a different refractive index. These reflections are referred to as Fresnel reflections. Fresnel reflections are a function of the refractive index difference of the two mediums and the incident angle of light at the interface.

## Flat Physical Contact Connections

When two connectors are mated to each other, the glass fibers will ideally make physical contact. This is where the term “PC” was coined. PC stands for “physical contact,” which just means that the fiber end faces within the connector physically mate to each other. In its most basic form, at this ideal connection, the return loss is a function of the difference of the refractive indexes of the two mated fibers.

Figure 1 shows two fibers mated together. One fiber has a refractive index $n_1$ and the second has a refractive index of $n_2$. As a note, when analyzing return loss at interface matings in this paper, it will be assumed the interfaces have no significant scratches, contamination, or imperfections of any concern outside of the topics discussed.

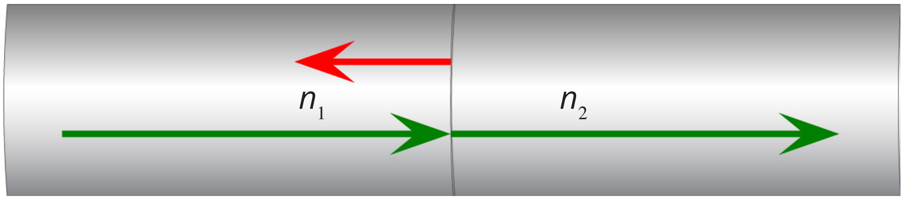


*Figure 1: Simple fiber to fiber mating*


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The simple equation that defines the return loss of this type of connection is:

$$RL(dB) = 10 * LOG\left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$$

Where: $n_1$,$n_2$ are the refractive indexes of medium one and medium two, respectively.

For a simplified case, the return loss of an open connector with a flat polish where a glass fiber interfaces with air, $n_1$ is close to 1.4673 for single mode fiber and $n_2$ is close to 1 for air. The return loss in this case can be calculated to be about -14.45dB (Figure 2).

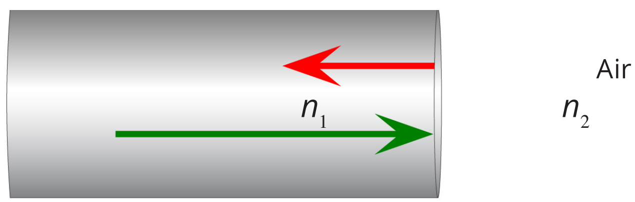


*Figure 2: Fiber to Air (n1=1.4673, n2=1), RL=-14.45dB*

For a more typical case, the two connectors mated to each other are assembled with fibers of similar construction. In the simplest case, the two connectors would be constructed with the same fiber. If each connector is assembled with the same fiber, then the refractive indexes ($n_1$, $n_2$) are equal.

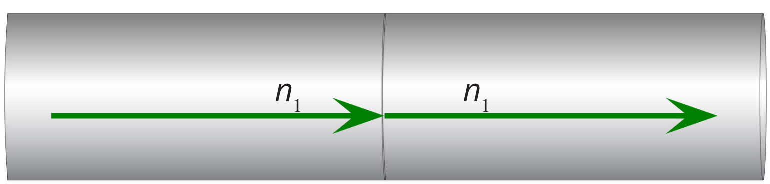


*Figure 3: Fiber-to-fiber mating with the same refractive index results in no reflected light*

With $n_1$ and $n_2$ equal, the numerator of Equation 1 becomes zero and the value for return loss on such a connection becomes a very large negative number (Log(0)→-∞), which simply means there is no reflection at all. However, in practice, it is known that a flat, physically contacting mating almost never exceeds -60dB, and is more typically between -45 to -60dB.

When mating two connectors with fibers of the same type the refractive index could vary by about ±0.0005 over a large population of fibers. These differences, when put through Equation 1 will still yield large RL values (~-70dB) depending on the refractive index mismatch. However, as stated above, measured return loss on mated, flat, physically contacting fibers rarely achieves above -60dB. Why is this? Why is the value in practicality so much less than in theory?

The simple model of two fibers with two different refractive indexes is not sufficient. There are other phenomena that can affect the refractive index of the fiber within the connector.

## *Refractive Index Changes Due to Polishing*

A common process during the assembly of a fiber optic patch cord is to polish the end face of the connectors on each end. When a connector is polished, the ferrule and fiber are ground down to shape and smooth the fiber for proper mating to another connector. This process, though, damages the fiber's end face. The damage at the surface creates a refractive index change on the end face of the fiber. This region has been referred to as a "damage layer."

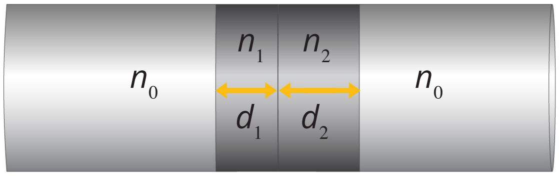


*Figure 4: Complex fiber to fiber mating with different refractive indexes and different damage layer depths.*

Figure 4 shows two fibers with the same refractive index, $n_0$, mated to each other. Each fiber has its own damage layer. The damage layer depths are $d_1$ and $d_2$ and the corresponding refractive indexes are $n_1$ and $n_2$ respectively. The mated return loss of such a connection is defined by the equation below:

$$RL = -log_{10}\left(\frac{\left[\left(\frac{n_1}{n_2}-\frac{n_2}{n_1}\right)n_0E\right]^2+\left[\left(\frac{n_0^2}{n_2}-n_2\right)G+\left(\frac{n_0^2}{n_1}-n_1\right)H\right]^2}{\left[2n_0F-\left(\frac{n_1}{n_2}-\frac{n_2}{n_1}\right)n_0E\right]^2+\left[\left(\frac{n_0^2}{n_2}+n_2\right)G+\left(\frac{n_0^2}{n_1}\mp\right)H\right]^2}\right)$$

*Equation 2*

Where:

$E=\sin\delta_1 \sin\delta_2$;

$F=\cos\delta_1 \cos\delta_2$;

$G=\cos\delta_1 \sin\delta_2$;

$H=\sin\delta_1 \cos\delta_2$;

$\delta_1=2\pi n_1 d_1/\lambda$;

$\delta_2=2\pi n_2 d_2/\lambda$;

$n_1$ and $d_1$ are the refractive index and depth of the "damage layer" of the first fiber;

$n_2$ and $d_2$ are the refractive index and depth of the "damage layer" of the second fiber;

$n_0$ is the refractive index of the fiber's core.

If the connectors undergo a similar polishing process, the calculation can be simplified. The damage layer is assumed to be the same, so the refractive index and depth of the layers can be treated as identical.


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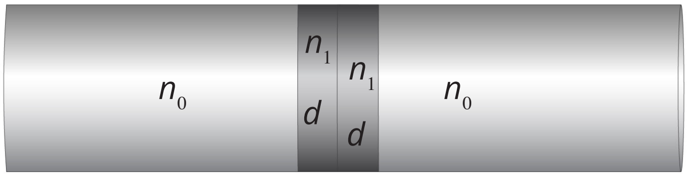


*Figure 5: Simplified PC-PC connection, with damage layers equal.*

The width of this layer and the resulting refractive index of this layer helps to define the mated return loss of two connectors. In the past, with somewhat crude polishing practices, this damage layer largely determined the resulting return loss of a mating. However, with modern polishing methods, the refractive index change and depth of this layer are minimal. Final polishing films have almost completely reduced this layer to be non-existent, which allows for return loss values of a mated pair to exceed -50dB on physically contacting connections. A typical damage layer on an ultra-physical contact (UPC) polished fiber is less than 10nm deep and the refractive index does not change by more than ~0.3%. Using these values, and assuming the damage layers are equivalent in the connection would yield return loss values close to -75dB. With modern polishing methods these values are still not able to be achieved. What else might be preventing the return loss of a PC connection to reach -65 to -75dB as Equation 2 may suggest is theoretically possible?

## Hertzian Contact Stress

To properly maintain mating after two connectors have made contact, most connectors have a spring inside the housing to hold the two ferrules in contact. The pressure the two opposing springs place on the two mated ferrules will gently deform the ferrules as well as the fiber in the ferrule. This deformation of the fiber will also cause the refractive index of the deformed section of the glass to change. This refractive index change can be viewed as adding to the refractive index change due to the damage layer. The refractive index change at the point of contact between two fibers is due to both the damage layer and this Hertzian contact stress.

### Fiber Protrusion

In the case of connectors that have a fiber protrusion (where the fiber sticks out of the ferrule), the contact force should not be too excessive to the point where the fibers deform so much that the refractive index changes dramatically. This dramatic change can significantly affect the return loss and insertion loss.

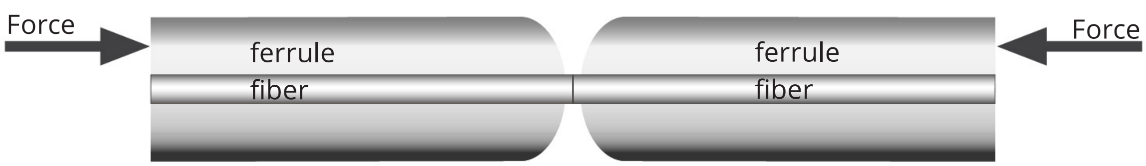


*Figure 6: Connectors with fiber protrusion at initial contact.*

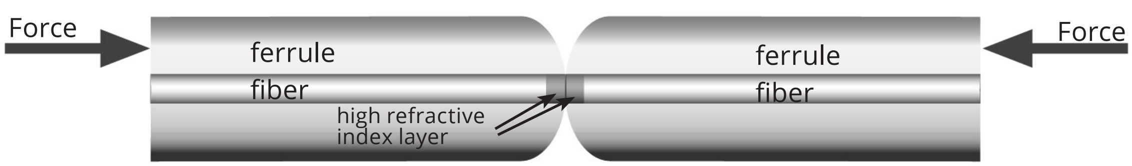


*Figure 7: Connectors with fiber protrusion fully mated showing a high index layer formed by the Hertzian contact stress.*


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Figure 6 above shows the initial contact of the protruded fibers. At this point there is no undue stress on the fiber that would result in a high index layer. The return loss would best be represented by Equation 1.

As the spring force continues to work on the connection the protruded fibers deform as the connection reaches equilibrium. This excess force on the fiber creates the high index layer as is pointed out in Figure 7.

### Fiber Undercut

In connectors that have an undercut geometry where the fiber is recessed inside the ferrule, the mating needs to overcome the undercut spacing to guarantee physical contact of the fibers. Figure 8 shows an undercut mating making initial contact with the two ferrules. At this point the two fibers have not made proper contact.

If the spring force is sufficient to overcome the undercut fibers, then the ferrule ceramic will deform as shown in Figure 9. At this point the two fibers make initial contact and the fibers have not yet deformed. In this instant during the mating process, there is no excess pressure on the fiber and no high index layer has been created due to the Hertzian contact stress. Assuming the damage layer is negligible, the return loss at this instant would be governed by Equation 1.

As is the case with most connectors, if the undercut is small, the spring force will continue to push the two connectors together. This excess spring force puts undue stress on the fiber resulting in a high index layer at the physical contact as shown in Figure 10.

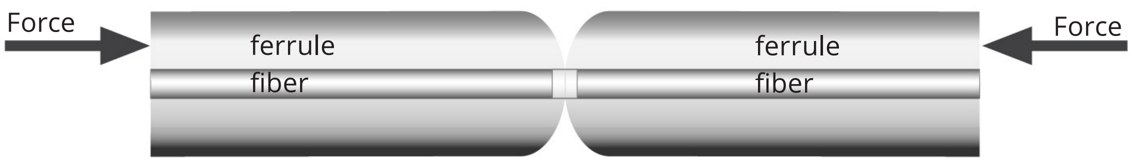


*Figure 8: Initial contact of undercut PC-PC mating resulting in an air gap.*

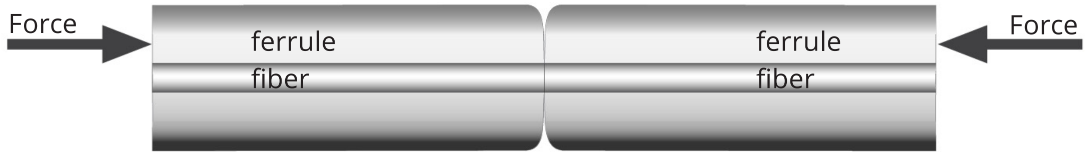


*Figure 9: PC-PC mating with pressure applied deforming the ferrule and fibers make contact.*

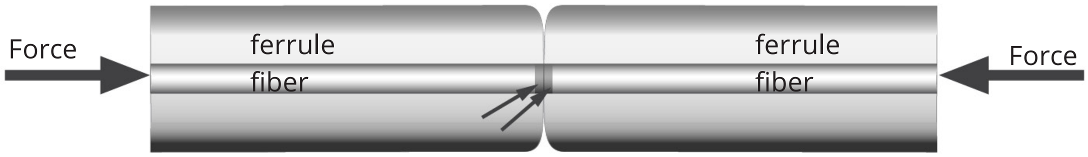


*Figure 10: Complete mating after all force is applied to connection. Fibers make contact and deform resulting in high index layers on both fibers' end faces.*

In looking at return loss associated with clean, flat-polished, physically contacting connections, the main cause of return loss is refractive index mismatches at the mating interface. These mismatches can come from various sources. They can come from different fiber types in the two connectors; however, it is likely that the two fibers in the mating have very similar refractive indexes, which should not lead to significant return loss. The larger factors


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for the refractive index mismatches and resulting return loss are due to the damage layer created during the polishing process as well as the compressive force that deforms the fiber during mating.

# Angled Physical Contact (APC) Connections

To achieve much lower return losses on physically mated pairs as well as on open connectors, the angle polishing process was introduced. Angle polished connectors are polished to an industry standard eight degrees. This eight-degree polish helps to dramatically reduce the amount of light that is reflected back towards source. What causes this reduction in return loss?

## *Non-Mated APC Open to Air*

With a perfectly polished eight-degree fiber end face left open to air, the incident light will still experience about a 96% transmission through the glass to air interface and a 4% reflection at the interface. This 4% reflection is equivalent to the 4% reflection that is experienced by an open flat fiber end face, however, in the case of the flat end face the reflected light is reflected directly back down the fiber towards the light source. In the case of the angle polished end face the reflected light is not reflected directly back down the fiber, but is reflected at an angle leading to the majority of the reflected light escaping the fiber through the cladding. A small percentage of the reflected light stays coupled in the fiber.

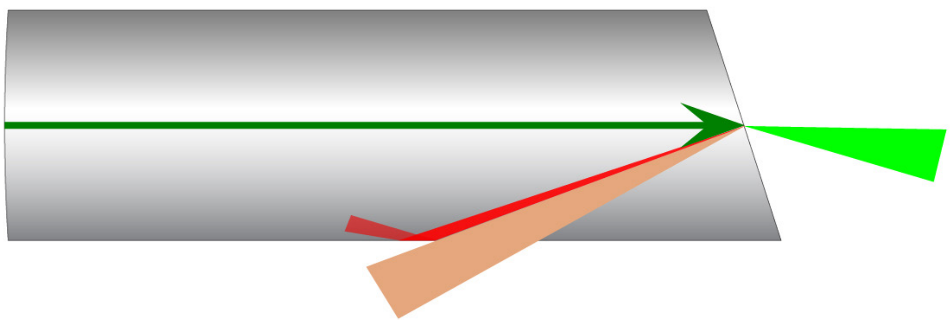

*Figure 11: Open APC polished fiber to air.*

When assessing the return loss of an angle polished fiber, there are two main considerations. There is the amount of light that is reflected due to the Fresnel reflection (could be glass to air or glass to glass) and there is a component that is due to the reflected angle of the light. The equation for the intrinsic return loss of an angled connection is shown in Equation 3. This equation closely approximates the return loss for angles that are smaller than 10°. For larger angles, the polarization of the light begins to alter the reflection magnitude at the Fresnel interface.

$$RL(\tau) = RL_0 + 10\frac{(\pi \cdot n_1 \cdot \omega_1)^2}{\lambda^2} \cdot log_{10}(e) \cdot (2 \cdot \tau)^2$$

*Equation 3*

where:

$\tau$ is the incident angle, which is also the angle of the polished interface

$\omega_1$ is the mode field radius of the fiber

$n_1$ is the refractive index of the fiber

$\lambda$ is the wavelength of light

$RL_0$ is the return loss due to the Fresnel reflection at the interface (Equation 2)


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In this equation, there are two terms. The first term, $RL_0$, is only related to the amount of light reflected due to the interface mating and the second term is associated with the amount of light lost on the reflection due to the angle of the interface.

The first term ($RL_0$) is dependent on the refractive index mismatches of whatever the fiber might be mated against (air, another fiber, etc.) as well as mismatches associated with a damage layer and Hertzian stress. This first term is essentially the same calculation for a flat connection as defined by Equation 2. If, for example, an angled fiber is open to air, the first term of the equation becomes -14.45dB, when using a refractive index of 1.4673 for n1 (glass) and 1 for n2 (air). The percentage and amount of light reflected at the interface is the same for the angled and flat case.

The second term is for the angle's effect on the return loss and how much reflected light remains coupled in the fiber back towards the source. This term is mainly based on angle of the polish, refractive index of the fiber, and fiber structure (mode field diameter) alone. It does not depend on the refractive index differences between the fibers or the medium the fiber will be mated against. This term is independent of whatever the connector is mated against.

For a standard fiber with a mode field diameter (MFD) of 10.2, a refractive index ($n_1$) of 1.4673 and operating at 1550nm, the second term results in -77.9dB of attenuation to the returned signal. This term is simply the angle's contribution to the return loss. The angle attenuates the returned signal by 0.00000162%. This attenuation is in addition to the attenuation associated with the mating.

If we use the same fiber with an angle polish and leave it open to air, the reflection due to the open-to-air fiber is ~-14dB or 4%. This 4% of light reflected at the glass-air interface combined with the 0.00000162% of reflected light that is guided in the fiber back towards the source results in 4% * 0.00000162% or 0.0000000648% of light that is guided back towards the source. This results in about 92dB of return loss.

For a simpler explanation using Equation 3 using optical power numbers see Figure 12.

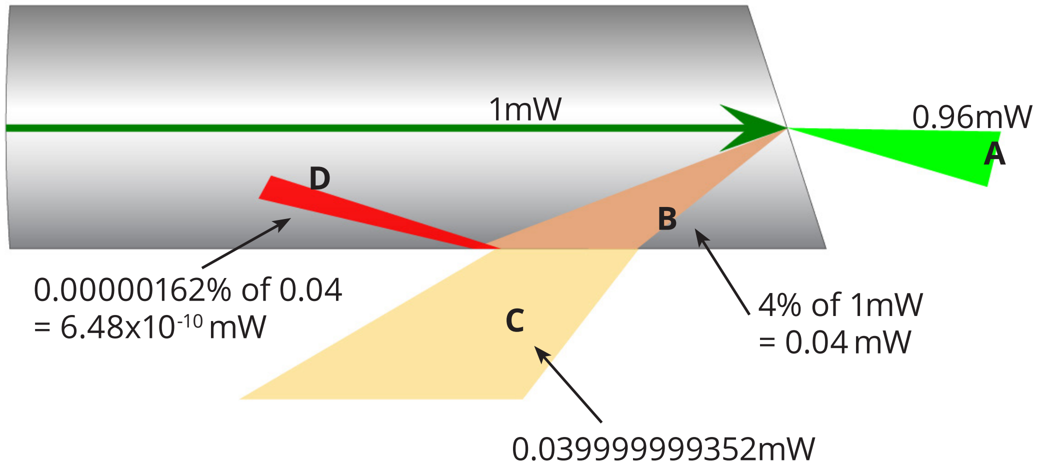


*Figure 12: Calculation of Open APC to air return loss.*


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Referring to Figure 12, if 1mW is incident on the angled interface, the glass is polished at a perfect flat 8° angle, and the interface is open to air leading to a 4% reflection, then 0.96mW is transmitted through the interface to air (A) and 0.04mW is reflected back into the fiber (B). Of the 0.04mW that is reflected back into the fiber, 0.00000162% is reflected at the core/cladding interface (D) and maintains coupled in the fiber which will propagate back towards the source. This leads to $6.48 * 10^{-10}\ mW$ of light traveling back towards the source (return loss). If 0.04mW reflected at the glass-air interface and $6.48 * 10^{-10}\ mW$ is coupled back into the fiber at the cladding interface, then the rest of the light escapes the fiber through the cladding (C), which would be:

$$0.04mW - 6.48 * 10^{-10}mW = 0.039999999352mW$$

Now to calculate the return loss of the light that is coupled back into the fiber, one can use the simple return loss equation:

$$RL(dB) = 10 * Log10\left(\frac{P_{refl}}{P_{inc}}\right)$$

*Equation 4*

Where $P_{refl}$ is the power reflected into the fiber and travels back towards the source and $P_{inc}$ is the power that is incident on the interface.

Entering 6.48*10 ^-10 mW for $P_{refl}$ and 1mW for $P_{inc}$ into Equation 4.

$$RL(dB) = 10 * Log10\left(\frac{6.48 * 10^{-10}mW}{1mW}\right)$$

$$RL = -91.88dB$$

## Mated APC to APC Connection

The above example explains an open-to-air angled fiber, however, if the angled fiber is mated against another angled fiber, then a similar calculation can be performed. As with a flat polished mating, this connection will have refractive index mismatches at the interface. These refractive index mismatches, again, are a combination of the polishing process and the force applied to the connection and the associated return loss can be approximated by Equation 2.

For comparison, it is worthwhile to look at a similar PC-PC connection's return loss and then look at the effect the angle has on the identical connection, except with an angle applied. An example PC connection is shown in Figure 13.

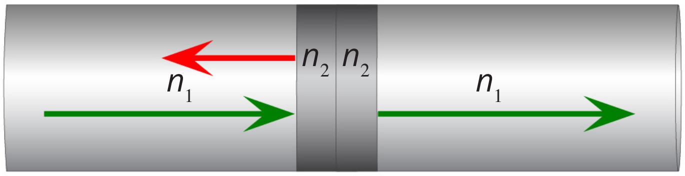


*Figure 13: PC-PC mating with a high refractive index layer on each interface.*

In this example, the assumption is that the high refractive index layer's width is identical for both fiber faces, the refractive index of the high index layer is identical, and the refractive index of the two fibers is identical. If this is


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assumed, then Equation 2 can be used to compute the theoretical return loss. Using: n1 = 1.4673, n2 = 1.4873, and d=10nm, we get about -54.3dB for return loss.

If the same mating (everything being equal) is analyzed, but with angled interfaces, then it would look something like this:

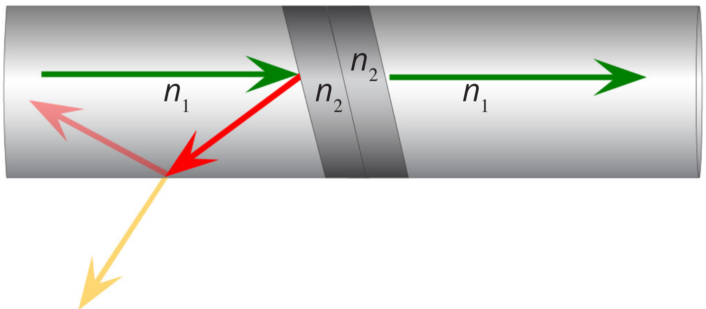


*Figure 14: APC-APC mating with high refractive index layers on each interface.*

Using the same values as in the previous example for n1, n2, and d, one still gets a reflected signal at the interface of -54.3dB. This reflected light is directed toward the cladding at 8° as well. As shown with the previous example of the APC fiber open to air, a certain percentage is lost at the core cladding interface and some is directed back toward the source. The percentage that is directed back toward the source is defined by Equation 3. As with the previous APC example, this percentage leads to another -77dB of return loss, in addition to the -54.3dB of return loss associated with the refractive index mismatch at the interface. The result is ~-121dB of return loss for this APC connection.

These are completely theoretical numbers and, of course, they assume perfectly flat matings between the two fibers. This is generally not the case. Typically, the fiber has a curvature to it, but under compression the curvature of the fiber is reduced. The purpose of calculating these sample matings is to illustrate that an APC mating greatly reduces the amount of light reflected back towards the source.

## Conclusion

Return loss at mated connections has three main contributions: the damage layer due to the polishing process of the fiber, the Hertzian contact stress at the fiber-to-fiber mating, and the angle polish of the connector.

The damage layer created by the polishing process, along with the Hertzian contact stress due to the spring force pressure applied to the ferrules to maintain physical contact, lead to a refractive index change at the interface. The theoretical return loss of this refractive index difference can be calculated using Equation 2. The calculated return loss is a function of the depth of the high refractive index layer as well as the actual refractive index of this layer.

A further reduction in return loss can be achieved by polishing the end faces at an angle. This angle reflects the light at the interface at an angle which causes a vast majority of the reflected light to escape the fiber through the cladding and only a small fraction of the reflected light maintains coupled in the fiber and travels back towards the source. The return loss of an angled mating is calculated using Equation 3. This equation is comprised of two terms: one that is determined by the high refractive index layer and one that is determined by the angle polished on the connector.


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