Refractive index discontinuities in fiber optic connectors

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Connector loss variability has an important impact on planning and developing fiber optics networks. Interdisciplinary design considering optical and contact mechanics phenomena at the interface between connected waveguides with physical contact is a key element in providing sound recommendations for technology. The authors focus on studying the influence of refractive index discontinuities occurring on fiber optic connectors with physical contact and suggest design and manufacturing approaches for controlling it.

(Received May 4, 2011; accepted May 11, 2011)

Keywords: Fiber optic connectors, Hertzian contact, Wave coupling loss, Interdisciplinary design

1. Losses in fiber optic connectors

Power losses in fiber optic connectors with physical contact are caused by a large number of factors such as: *End Gaps*, *Core* and *Numerical Aperture Mismatch*, *Axial Run-out,* End Angle, *End-face Roughness*, *Dust*, etc. [1].

End gaps between fiber optic connector end-faces are particularly important because they cause both Optical Return Loss (RL) and Optical Insertion Loss (IL). Minimizing RL on high-speed DWDM systems is particularly important in stabilizing the central wavelength of the laser sources. RL is usually expressed as the ratio between the input power P_i and the reflected power P_r and is expressed in decibels (dB) [2]:

$$RL = 10\log_{10}\frac{P_i}{P_r} \qquad (01)$$

The optical return loss RL can be reduced significantly by ultra polishing end-faces in contact as in UPC connectors and even by angling them as schematically represented in Figure 1, as in APC connectors. Most authors agree with values of 35 dB to 55 dB for UPC connectors and 55 dB to 70 dB for APC connectors [2].

Optical Insertion Loss or IL is the direct result of inserting a device in the transmission line and is defined as the ratio between the signal power before attaching a device, P_t, and the signal power received after inserting the device, P_r , and is expressed in decibels [2]:

$$IL = 10\log_{10}\frac{P_t}{P_r} \qquad (02)$$

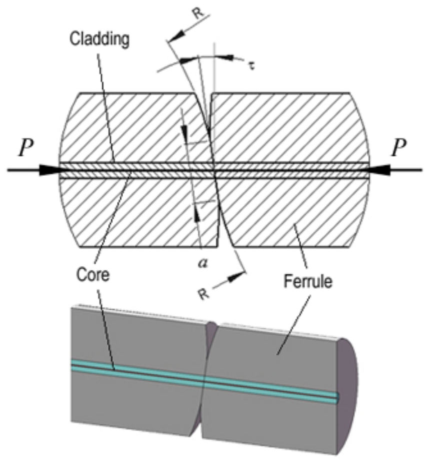

Fig. 1. Angled end-faces in physical contact.

The authors investigate the effects of refractive index discontinuities on connectivity performance of SC PC connectors for single mode Corning SMF 28 step-index fiber working at the wavelength λ =1550 nm. The 3D model of typical SC PC connectors is represented in Fig. 2. Under the load of a helical compression spring, the system ferrule – fiber is pressed against another similar system of the same type. The core and cladding of the fiber are made of fused silica glass (SiO_2) of high chemical purity. Its optical specifications related to the paper are as follows:

- Mode-Field Diameter MDF at λ =1550 nm: 10.4±0.8 μm
- Core Diameter: 8.2 μm
- Cladding Diameter: 125.0±0.7 μm

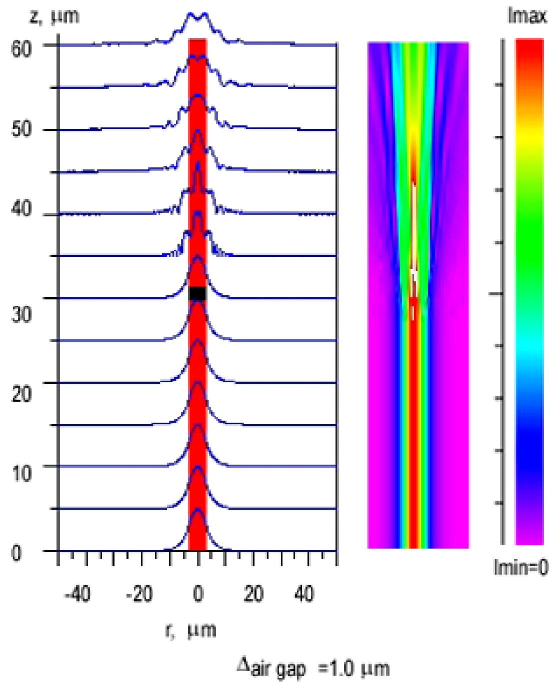

Fig. 4. BMP with air-gap Δ=1μm.

Fig. 3 shows a practically non-altered beam mode profile after propagation through an air-gap Δ=0.2μm. A seriously altered beam mode profile after propagation through an air-gap Δ=1μm is shown in Fig. 4. The simulation is performed in BeamProp and shows non-acceptable degradation levels of the beam mode profile for cylindrical air-gaps Δ>0.5-0.6μm.

3. Contact mechanics in connectors

In fiber optic connectors with physical contact, localized stresses develop as the two curved surfaces in contact deform slightly under the normal load. The deformations are dependant of the geometry of surfaces in touch, their modulus of elasticity, and the applied normal load [5]. The following assumptions are considered for Hertzian contacts:

- Strains are within the elastic limits
- Surfaces are frictionless, continuous and non-conforming
- Contact area is much smaller than the effective radius of the surfaces involved

The study of contact becomes complex if these assumptions are violated and the contact is considered non-Hertzian.

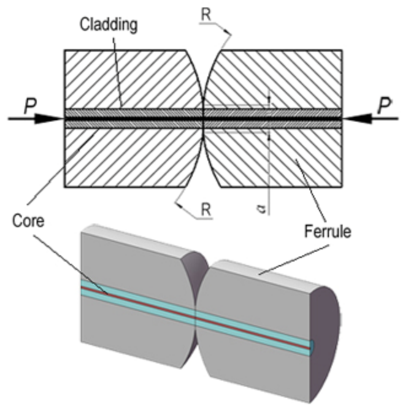

Fig. 5. Schematic representation of ferruled fibers in contact.

For a Hertzian contact between two spherical surfaces of radii R_1 and R_2, the area of contact has a circular shape of radius a and the distribution of pressure as a function from the center of the circle is given by [5]:

$$p(r) = p_0\left(1 - \frac{r^2}{a^2}\right)^{\frac{1}{2}} \qquad (05),$$

p_0 is the maximum contact pressure and is given by:

$$p_0 = \frac{3P}{2\pi a^2} = \frac{1}{\pi}\left(\frac{6PE^{*2}}{R_e^2}\right)^{\frac{1}{3}} \qquad (06)$$

In fiber optic connectors the materials in contact are identical and have the same Poisson ratio ν. In equation (06), E^* represents the effective elastic modulus, given by:

$$E^* = \frac{E}{2(1-\nu^2)} \qquad (07)$$

R_e represents the effective radius, given by:

$$R_e = \frac{R_1 R_2}{R_1 + R_2} \qquad (08)$$

The radius of contact area is related to the applied load P by the equation:

$$a = \left(\frac{3PR_e}{4E^*}\right)^{\frac{1}{3}} \qquad (09)$$

Finally, the depth of indentation is given by the equation:

constant of material, p is the pressure at $M_{(\rho,\theta)}$, v is the linear speed in $M_{(\rho,\theta)}$, τ is the time from the start of the process and T is the total polishing time.

The spherical shape of the end-face is a result of the interaction between the ferrule, the fiber and the rubber pad. The initial geometry of the ferrule, the nature of the materials involved, and the polishing procedures are all important.

Polishing experiments with a variety of materials like aluminium oxide, chrome oxide, cerium oxide, etc., proved to offer less satisfactory results compared to diamond. Diamond lapping films provide a dependable finish to surfaces of elevated hardness like zirconium oxide.

Wet polishing with 0.1μm diamond films and type I deionised water provides the optimal settings for the desired low roughness, as illustrated in Fig. 8. The microstructure of the surfaces is clearly visible at a magnification of 400X.

Geometry parameters characterizing polished connectors like radius of curvature, offset of polish, undercut or protrusion should be evaluated on non-contact and fully automatic interferometric microscopes. The system provides 3D topographic information regarding the geometry of the surface inspected. Real time access to the topology of the end-face gives the user full control of the polishing processes.

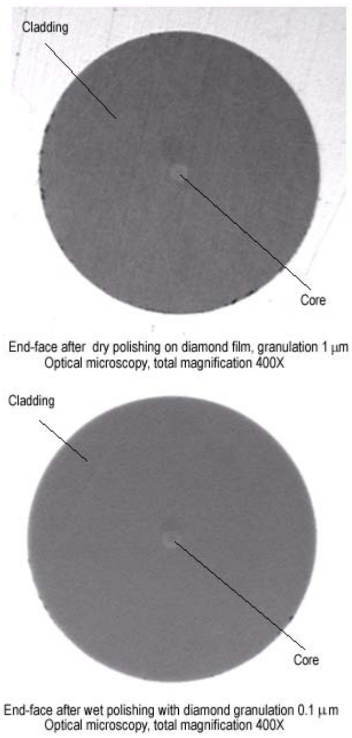

Fig. 8. End-face microscopy, magnification 400X.

Interferometric topography of polished end-face connector performed on such system is illustrated in Fig. 9. The user has real time access to valuable information regarding radii of curvature, spherical height, linear and angular offset, and ferrule and fiber roughness.

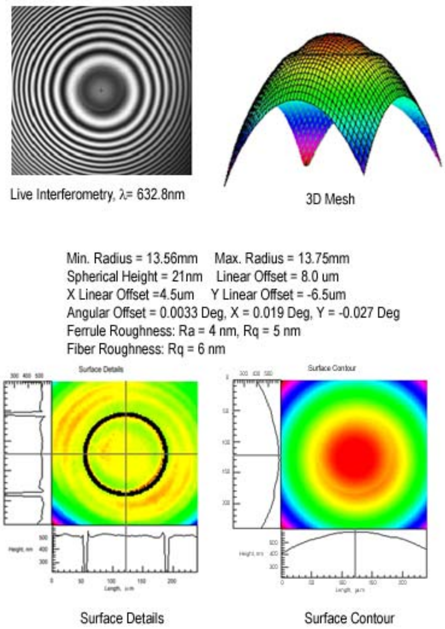

Fig. 9. Interferometric inspection of polished end-face.

5. Concluding remarks

The authors emphasize the benefits of interdisciplinary efforts in developing optical waveguide connectors with physical contact and focus on the influences of refractive index discontinuities on transmission losses. Numerical modelling of such discontinuities using the finite difference beam propagation method allows accurate evaluations of the wave propagation through the air-gaps. Contact mechanics facilitates the understanding of loaded interface phenomena and suggests optimized end-face geometries. Finally, the authors comment on specific polishing challenges, and suggest consistent solutions.

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