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Mechanical performance of physical-contact, multi-fiber optical connectors: Finite element analysis and semi-analytical model

Esteban B. Marin, Hieu V. Tran, Andrey Kobyakov *

Optical Connectivity Solutions, Corning Optical Communications, Hickory, NC 28602, United States

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ABSTRACT

Three-dimensional finite element analysis of physical-contact, multi-fiber optical connector was used to characterize fiber-to-fiber contact and support the development and validation of a semi-analytical model (SAM) for the contact force. This contact behavior is determined by the elastic deformation of the system components (ferrule, fibers, and bonding adhesive) and the classical Hertzian contact at the fiber tips – effects that ultimately define the axial compliance of the system. Two 3-D finite element models for a 12-fiber connector are constructed to study the contact of two connectors, and the specific numerical simulations are carried out to generate input data to SAM, confirm the main assumptions made in its development, and numerically validate the predictions for the contact force. These simulations mainly consider non-uniform fiber height profiles and different end-face fiber tip geometries characterized by their radius of curvature. The numerically validated SAM is then used to study some performance aspects of multi-fiber connectors as related to the required contact force, namely, finding fiber height profiles that require minimum contact force and evaluating the throughput of polishing processes assuming a target contact force. Predictions are supported by Monte Carlo simulations and associated with current profile geometry metrics.

1. Introduction

Optical connectors are important mechanical components in fiber optic communication systems [1,2]. They simplify the fiber termination process (connection between optical fiber cables and optical devices in electronic equipment) for single-mode (SM) and multi-mode (MM) fibers. Currently, single-fiber and multi-fiber connectors are used in these systems depending on the specific application, and different connector designs have been developed for such purposes. Many of these designs rely on fiber-to-fiber physical contact (PC), a phenomenon highly dependent on the connector's interface geometry, and typically induced by the spring force in spring loaded connectors. Good PC guarantees a continuous, dependable light signal transmission, resulting in a good optical performance characterized by insertion and reflection loss.

Initial implementations of optical transmission systems used a single-fiber, PC connector, whose main components were a cylindrical ceramic ferrule with a glass fiber running through its center and fixed to the ferrule with a bonding agent. By then, many studies were performed to understand their mechanical and optical performance [3–11]. Most of these studies focused on describing the interface mechanics of mated connectors to understand their contact response and establish criteria and dimensional limits for the end-face geometry required to maintain reliable PC. Different analytical, numerical, and experimental approaches were used to study connectors' behavior considering various environmental and mechanical conditions.

The need for high-density interconnect applications, such as infrastructures for data centers and storage area networks, triggered the development of multi-fiber connectors. These physical contact connectors effectively distribute a large number of parallel fibers, either SM or MM, with a single connection, providing significant space and cost savings over the single-fiber connectors. These are commonly referred to as mechanical transferrable (MT) or multi-fiber push-on (MPO) connectors, with the name MTP® connector designating an improved design over the generic MPO connector.

Over the past decade, the MTP/MPO connectors have become an industry standard for parallel optics links. They were used as interfaces for VCSEL-based transceivers (see, e.g., [12] for an overview), optical backplane connectors to printed circuit board integrated polymer waveguides [13,14], pluggable connectors for optical

* Corresponding author.
E-mail addresses: marineb@corning.com (E.B. Marin), kobyakova@corning.com (A. Kobyakov).

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coupling between single-mode fibers and grating couplers on silicon chips [15] or even in optical assemblies for space flight environments [16]. The 12-fiber version of MTP connector is the most commonly used one, however, large count multi-row connectors do also exist [17].

Good optical performance over the lifetime of a multi-fiber connector requires consistent, stable PC between all fiber pairs in mated connectors, and factors affecting this condition are also related to the connector interface geometry, namely, fiber height profile, fiber tip shape, and the ferrule polishing angle. Large fiber tip radii, non-uniform fiber height distributions, and large polishing end face angles of the ferrule may result in a larger contact force than the force supplied by the connector spring, resulting then in poor PC and high insertion loss (IL). The effect of imperfect physical contact on connector performance was extensively studied in the past, see, e.g., a recent study of Ref. [18] and references therein.

Mechanical studies of multi-fiber connectors with SM fibers were performed in [19,20] by using a three-dimensional (3-D) finite element model of a 2-fiber ferrule to characterize the effect of some geometric parameters (ferrule's end-face radius of curvature, ferrule's end-face angle, and fiber protrusions) on the deformation and strains in the ferrule during contact. However, the details of how the fibers and epoxy were modeled were not discussed. A simplified axisymmetric finite element model of the MTP connector with MM fibers was used in [21–23] to support the development of a theoretical model for predicting the contact force during mating of a 12-fiber MTP connector. The model of Ref. [21] described the contact between a rigid plate and a connector and solely considered the axial stiffness of the system components (ferrule, fiber, and epoxy). Predictions of the theoretical model compared favorably with experimental data. This model has been extended in [22,23] to include mating of dissimilar connectors and in [24] to include the rotational stiffness of the ferrule. Some connector design solutions were proposed based on that work [25,26]. Other modeling work on multi-fiber connectors focused on using statistical approaches (Monte Carlo) to predict the induced optical losses due to alignment tolerances of various geometrical features of the connector [22,23,27–29], and design-of-experiment studies to determine design constraints during manufacturing of multi-fiber ferrules [30].

This work presents the finite element analysis (FEA) of 12-MM fiber MTP/MPO connectors to study their fiber-to-fiber contact behavior during mating. Two 3-D finite element models of mated connectors are constructed and used to carry out specific simulations to support the development of a semi-analytical model (SAM) for multi-fiber connectors. This theoretical model is linear elastic. It effectively computes the evolution of both the contact force and fiber deformation as fiber pairs in mated connectors get in contact. The derivation of the governing equations considers mainly the axial compliance of the system components (ferrule, fibers, epoxy), including the Hertzian contact at the fiber tips and the elastic foundation effect, while neglecting any source of the rotational compliance of the system, e.g., the ferrule's end-face angle. Although a version of the SAM was presented in Ref. [21], the current work extents its applicability by (i) devising an approach to analyze mated connectors with dissimilar fiber height distributions, (ii) giving a comprehensive numerical verification/validation using numerical results from the 3-D FEA models of the MTP connector, and (iii) employing the model to study specific aspects of multi-fiber connectors, including the optimization of fiber height profiles for minimum contact force and the evaluation of the throughput of polishing processes using statistical tools.

The paper starts with a description of the 3-D FEA models of the MTP connector, followed by the numerical computation of the load-displacement relationship for the glass fiber which includes ferrule deformation, also referred to as the foundation effect [21], and the derivation of the SAM for the contact force. An extensive numerical validation of the SAM is then presented, justifying its use to model the mating process of two dissimilar connectors. Applications of the theoretical model are then given followed by a short summary of the work.

2. Finite element model of the MTP connector

Details of the internal geometry of the MTP connector highlighting the main components of interest are presented in Fig. 2.1a. The ferrule has a rectangular end-face of 2.45 mm $\times$ 6.4 mm, a depth of 8 mm, and contains one fiber array with twelve 125 μm diameter fibers on 250 μm centerline spacing. The glass fibers, protruding from the ferrule's end-face, are fixed to the micro-holes (diameter of about 126 μm) by a thin layer of epoxy. The ferrule is generally injection-molded from a highly glass-filled polyphenylene sulfide (PPS) resin, and it is spring-loaded to maintain fiber-to-fiber physical contact when two connectors are engaged. Precision alignment between mating connectors is attained with non-interference (non-zero gap), dual guide pin and bore arrangement. One connector usually houses both guide pins (male ferrule), while the other ferrule (female ferrule) receives the pins. Auxiliary (short) pins at the back of the female ferrule support the alignment process of the ferrules. Male and female ferrules have identical geometry. For notation purposes, the assembly composed of the ferrule, fibers and epoxy will be referred here as the MPO/MTP connector.

A 3-D high-fidelity finite element model of the ferrule is constructed to analyze its mechanical response with regard to contact when two connectors are mated, see Fig. 2.1b. The ferrule is partitioned into three cells (front, middle, back) to allow the use of a refined mesh in the area of interest (ferrule's front face), while the other cells can be discretized with a coarse mesh. Linear hexahedral finite elements (abaqus type C3D8R) are mostly used to discretize the geometry, with linear tetrahedral elements (abaqus type C3D4) used to fill parts hard to mesh with brick elements. The three cells are joined with tie constraints. The fibers, which protrude from the front-face of the ferrule, and epoxy layers, which bond the fibers to the ferrule, are also meshed with C3D8R elements, using a refined mesh in the area of interest (contact zone). Bonding between fiber-epoxy and epoxy-ferrule is modeled with tie constraints. The spring force, typically ranging from 6 to 10 N for these connectors, is distributed at the back surface of the ferrule using distributing coupling constraints. The guide pins and auxiliary pins are modeled as rigid bodies using analytical surfaces. The elastic material properties of the system components (ferrule, glass fiber, and epoxy) at room temperature are also given in Fig. 2.1b. A friction coefficient of zero is assumed for all contacting surfaces.

The above model of the ferrule, fibers, and epoxy is used to build two finite element models of the MTP connector to describe its response during mating. These models are denoted as ferrule-plate model and two-ferrule model, as indicated in Fig. 2.2. In principle, the first model can be used to represent the mating of two identical connectors, where due to the symmetry of the arrangement, one connector has been replaced by a rigid flat plate. As will be shown below, this model can also be used to describe the mating of two connectors with dissimilar height profiles provided that an effective fiber height protrusion for each fiber is used. However, this model will not be able to realistically represent the gap between the guide pin and pin bore. On the other hand, the second model is able to explicitly characterize the mating of two connectors with both dissimilar fiber height distributions and guide pin-pin bore gap.