Modeling VCSEL-to-SSMF Butt-Coupling For Enhanced Efficiency Using COMSOL Multiphysics®

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Abstract

This study presents a numerical investigation of optical butt-coupling between Vertical-Cavity Surface-Emitting Lasers (VCSELs) operating at 850 nm and Standard Single-Mode Fiber (SSMF), a widely adopted configuration in cost-effective, high-speed optical interconnects, especially in Radio-over-Fiber (RoF) systems for 5G and beyond.[1] As demand for compact and low-latency photonic solutions grows, optimizing the coupling efficiency between light sources and transmission fibers is essential to ensure signal integrity, reduce insertion loss, and support scalable network deployment. However, coupling VCSELs to SSMFs is inherently challenging due to modal mismatch and alignment sensitivity. Modal noise, caused by the excitation of higher-order modes such as LP_{11}, degrades signal quality and reduces RF link performance.[2] Traditional mitigation methods—like tapered fibers, splitters, or mode filters—help suppress higher-order modes but increase system complexity and cost. Butt-coupling remains an attractive solution for its simplicity but demands high alignment precision to maintain low loss and modal purity.[3]
To address this, a fully parametric 2D wave optics model was developed in COMSOL Multiphysics® 6.3 using the Electromagnetic Waves, Beam Envelopes (EWBE) interface from the Wave Optics Module.[4] A 2D approach was chosen under the assumption of perfect circular symmetry. This method, based on the Finite Element Method (FEM), offers computational efficiency and accurate modeling of wave propagation in weakly varying guiding structures like coupling regions.[5]
The out-of-plane vector formulation was selected to capture the electromagnetic field components normal to the simulation plane. This method allows efficient evaluation of guided modes, including potentially higher-order mode behavior.
The model includes the VCSEL emission field, an adjustable air gap, and the SSMF core, with Perfectly Matched Layers (PMLs) applied at the domain boundaries to absorb reflections (as you can see in picture 1.
The model evaluates key parameters: lateral displacement ($\Delta y = \pm 6$ μm), air gap distance ($\Delta x = 10$-40 μm), and angular tilt ($\alpha = 0°$-$4°$). The Optical Coupling Efficiency (OCE) was quantitatively computed through overlap integrals between the VCSEL-emitted field and the fiber's guided LP_{01} and LP_{11} modes. Additionally, the extinction ratio (ER), defined as the square of the ratio between the sum and difference of the modal powers of LP_{01} and LP_{11}, is used to quantify modal purity, which is critical for minimizing intermodal dispersion in RoF links.[6] Simulation results show that even minor angular misalignments ($\alpha \geq 2°$) significantly degrade and cause sharp drops in OCE and increase LP_{11} excitation, raising ER values and degrading overall performance. Under optimal alignment ($\alpha = 0°$, $\Delta y = 0$ mm), the OCE values are above -1 dB (equivalent to over 80% coupling efficiency). At 4° tilt, coupling efficiency falls sharply (below the -1 dB threshold), and ER rises markedly.
Figures support these findings: Fig. 1 shows the modelled geometry; Fig. 2 plots OCE versus α and Δx-, and depicts ER variation with misalignment. These results are directly applicable to the design of robust and efficient RoF photonic interconnects, where high-speed performance and compact integration are critical for next-generation telecom infrastructure.

Reference

Reference

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