

Contents

| | |
|-----------------------------------------------------------------------------|----|
| 1. Introduction | 1 |
| 1.1 An Overview of Fusion Splicing and Its Applications | 1 |
| 1.2 The Fusion Splicing Process | 3 |
| 1.3 Essential Optical Fiber Concepts | 8 |
| 1.3.1 Optical Characteristics | 8 |
| 1.3.2 Material and Mechanical Characteristics of Silica Fibers | 13 |
| 1.4 Alternatives to Fusion Splicing | 15 |
| 1.5 Fusion Splices in the Optical Network | 17 |
| 1.6 A Brief History of Fusion Splicing | 21 |
| 1.7 The Frontiers of Fusion Splicing | 23 |
| 1.8 Summary | 25 |
| 2. Fiber Preparation and Alignment | 27 |
| 2.1 Stripping | 27 |
| 2.1.1 Fiber Coatings | 28 |
| 2.1.2 Mechanical and Thermo-Mechanical Stripping Techniques | 31 |
| 2.1.3 Chemical Stripping Techniques | 33 |
| 2.1.4 Vaporization Stripping Techniques | 34 |
| 2.2 Cleaving | 35 |
| 2.2.1 Cleaving Techniques and Hardware | 36 |
| 2.2.2 Basic Cleaving Principles | 36 |
| 2.2.3 Cleave Defects | 39 |
| 2.2.4 The Importance of Cleave Quality | 40 |
| 2.3 Alignment | 42 |
| 2.3.1 Passive Alignment | 43 |
| 2.3.2 Image-Based Active Fiber Alignment | 43 |
| 2.3.3 Transmitted-Power Based Active Fiber Alignment | 44 |
| 2.3.4 Light-Injection and Detection (LID) Technology | 46 |
| 2.4 Summary | 47 |

| | |
|---------------------------------------------------------------------------------------|-----|
| 3. Mechanics of Fusion Splicing | 49 |
| 3.1 Heat Transfer During Fusion Splicing | 49 |
| 3.1.1 Arc-Discharge Heating | 50 |
| 3.1.2 Heat Flow | 52 |
| 3.2 Mechanical Forces During Fusion Splicing | 57 |
| 3.2.1 Compressive, Tensile, and Bending Forces | 58 |
| 3.2.2 Surface Tension and Viscosity | 62 |
| 3.2.3 Implications for Core Alignment | 65 |
| 3.2.4 Fusion Splice Duration | 67 |
| 3.2.5 Neckdown, Dissimilar Fiber Diameters, and Dissimilar Fiber Viscosities | 68 |
| 3.2.6 Bubbles, Airlines, and Air Holes | 70 |
| 3.3 Dopant Diffusion | 73 |
| 3.3.1 Theory of Dopant Diffusion | 74 |
| 3.3.2 Dopant Diffusion Coefficients | 79 |
| 3.3.3 Diffusion Examples | 80 |
| 3.4 Stress and Strain | 82 |
| 3.4.1 Source of Stress and Strain in Optical Fibers | 83 |
| 3.4.2 Fusion Splicing and Its Relationship to Residual Stress and Strain | 86 |
| 3.5 Summary | 88 |
| | |
| 4. Optics of Fusion Splicing | 91 |
| 4.1 Modal Description of Fusion Splices | 93 |
| 4.1.1 The Scalar Wave Equation | 93 |
| 4.1.2 Modes | 96 |
| 4.1.3 The Scattering Matrix | 99 |
| 4.1.4 The Overlap Integral | 104 |
| 4.1.5 The Reflectance of Fusion Splices | 106 |
| 4.2 The Optics of Single-Mode Fiber Fusion Splices | 108 |
| 4.2.1 The Mode Field Diameter | 110 |
| 4.2.2 The Gaussian Approximation | 111 |
| 4.2.3 Reflectance of Single-Mode Fusion Splices | 116 |
| 4.2.4 Modal Noise and Single-Mode Fiber Splices | 116 |
| 4.3 The Optics of Multimode Fusion Splices | 119 |
| 4.3.1 Propagation Characteristics | 119 |
| 4.3.2 Splice Loss Approximation Formulae | 121 |
| 4.3.3 Reflections from Multi-Mode Fusion Splices | 123 |
| 4.3.4 Fusion Splices Between Single- and Multimode Fibers | 123 |
| 4.4 The Beam Propagation Method (BPM) | 124 |
| 4.4.1 Introduction to BPM | 124 |
| 4.4.2 The Transparent Boundary Condition | 128 |
| 4.4.3 Mode Solving with BPM | 129 |

| | | |
|-----------|-----------------------------------------------------------------------|------------|
| 4.4.4 | Computing Splice Loss with BPM | 130 |
| 4.4.5 | A Practical BPM Example | 131 |
| 4.5 | Summary | 134 |
| 5. | Splice Loss Estimation and Fiber Imaging | 137 |
| 5.1 | Fusion Splice Imaging and Image Processing | 139 |
| 5.1.1 | The Imaging System | 139 |
| 5.1.2 | Introduction to Fiber Imaging | 141 |
| 5.1.3 | Characteristics of Fiber Images | 141 |
| 5.1.4 | Basic Image Processing | 146 |
| 5.2 | Loss Computation | 147 |
| 5.2.1 | Introduction to Coupled-Mode Theory | 148 |
| 5.2.2 | Coupled-Mode Theory in a Single-Mode Fiber: Microbend Theory | 151 |
| 5.2.3 | Coupled-Mode Theory for Loss Computation | 154 |
| 5.3 | Summary | 160 |
| 6. | Splice Strength, Reliability, and Packaging | 161 |
| 6.1 | Introduction to Splice Strength and Reliability | 162 |
| 6.2 | Crack Growth Theory | 165 |
| 6.3 | Characterizing Splice Failure Strength: Weibull Statistics | 168 |
| 6.4 | Theory of Proof Testing for Long-Term Reliability | 172 |
| 6.5 | Proof Testing Methods and Hardware | 176 |
| 6.6 | Splice Packaging | 177 |
| 6.6.1 | Splice Recoating Technology | 178 |
| 6.6.2 | Rigid Splice Protectors and Splints | 180 |
| 6.7 | Summary | 181 |
| 7. | Splice Measurement and Characterization | 183 |
| 7.1 | Transmission Measurements | 184 |
| 7.1.1 | Insertion Loss and Cutback Measurements | 184 |
| 7.1.2 | The “Pre-Splice” Technique | 187 |
| 7.1.3 | The Two-Splice Technique | 187 |
| 7.1.4 | Spectral Splice Loss Measurements | 189 |
| 7.2 | Reflection Measurements | 189 |
| 7.2.1 | Optical Continuous Wave Reflectometers (OCWRs) .. | 190 |
| 7.2.2 | Optical Time-Domain Reflectometer (OTDR) Measurements | 191 |
| 7.2.3 | High Resolution Reflection Measurements | 197 |
| 7.3 | Refractive Index Profiling of Fibers and Fusion Splices | 199 |
| 7.4 | Summary | 202 |

| | |
|-----------------------------------------------------------------------------|-----|
| 8. Splice Process Optimization and Special Splicing Strategies | 203 |
| 8.1 Design of Experiments for Splice Optimization | 204 |
| 8.1.1 The Splice Parameter Space | 205 |
| 8.1.2 Orthogonal Arrays | 206 |
| 8.1.3 Example Splice Optimization | 210 |
| 8.2 Special Splicing Strategies | 214 |
| 8.2.1 Fire Polishing and Arc Scanning | 214 |
| 8.2.2 Bridge Fibers | 215 |
| 8.2.3 Dopant Diffusion and TEC Splices..... | 217 |
| 8.2.4 Low-Temperature Splices | 220 |
| 8.2.5 Offset Heating | 221 |
| 8.2.6 Tapered Splices | 222 |
| 8.2.7 Fattened Splices..... | 226 |
| 8.3 Summary..... | 226 |
| 9. Fusion Splicing of Specialty Fiber | 229 |
| 9.1 Non-Zero Dispersion Shifted Fibers | 229 |
| 9.1.1 Introduction to NZ-DSF..... | 230 |
| 9.1.2 Special Splicing Considerations for NZ-DSF..... | 230 |
| 9.2 Polarization-Maintaining Fibers | 231 |
| 9.2.1 Introduction to PM Fibers | 232 |
| 9.2.2 Cleaving Considerations for PM Fibers | 233 |
| 9.2.3 Polarization Crosstalk and Polarization Extinction Ratio | 234 |
| 9.2.4 PM Fiber Alignment..... | 237 |
| 9.3 Erbium-Doped Fibers | 240 |
| 9.3.1 Introduction to Erbium-Doped Gain Fibers | 241 |
| 9.3.2 Strategies For Low-Loss EDF Fusion Splicing | 242 |
| 9.3.3 Loss Measurement of Erbium-Doped Fiber Splices | 244 |
| 9.4 Dispersion-Compensating Fibers | 244 |
| 9.4.1 Introduction to Dispersion-Compensating Fibers | 245 |
| 9.4.2 Splicing Strategies for Dispersion-Compensating Fibers | 246 |
| 9.5 Microstructured Fibers | 248 |
| 9.5.1 Types of Microstructured Fibers | 248 |
| 9.5.2 Fusion Splicing Microstructured Fibers | 249 |
| 9.6 Summary..... | 253 |
| 10. Splicer Hardware: State of the Art | 255 |
| 10.1 Introduction to Splicer Hardware | 256 |
| 10.2 Field Splicers | 256 |
| 10.3 Factory Splicers | 259 |
| 10.4 Research and Laboratory Splicers..... | 264 |
| 10.5 Summary..... | 266 |

| | |
|------------------------------------------------------------------------------------|-----|
| Appendix A: List of Mathematical Symbols | 267 |
| Appendix B: List of Abbreviations | 275 |
| Appendix C: List of Relevant Published Standards and Requirements | 277 |
| References | 279 |
| Index | 301 |