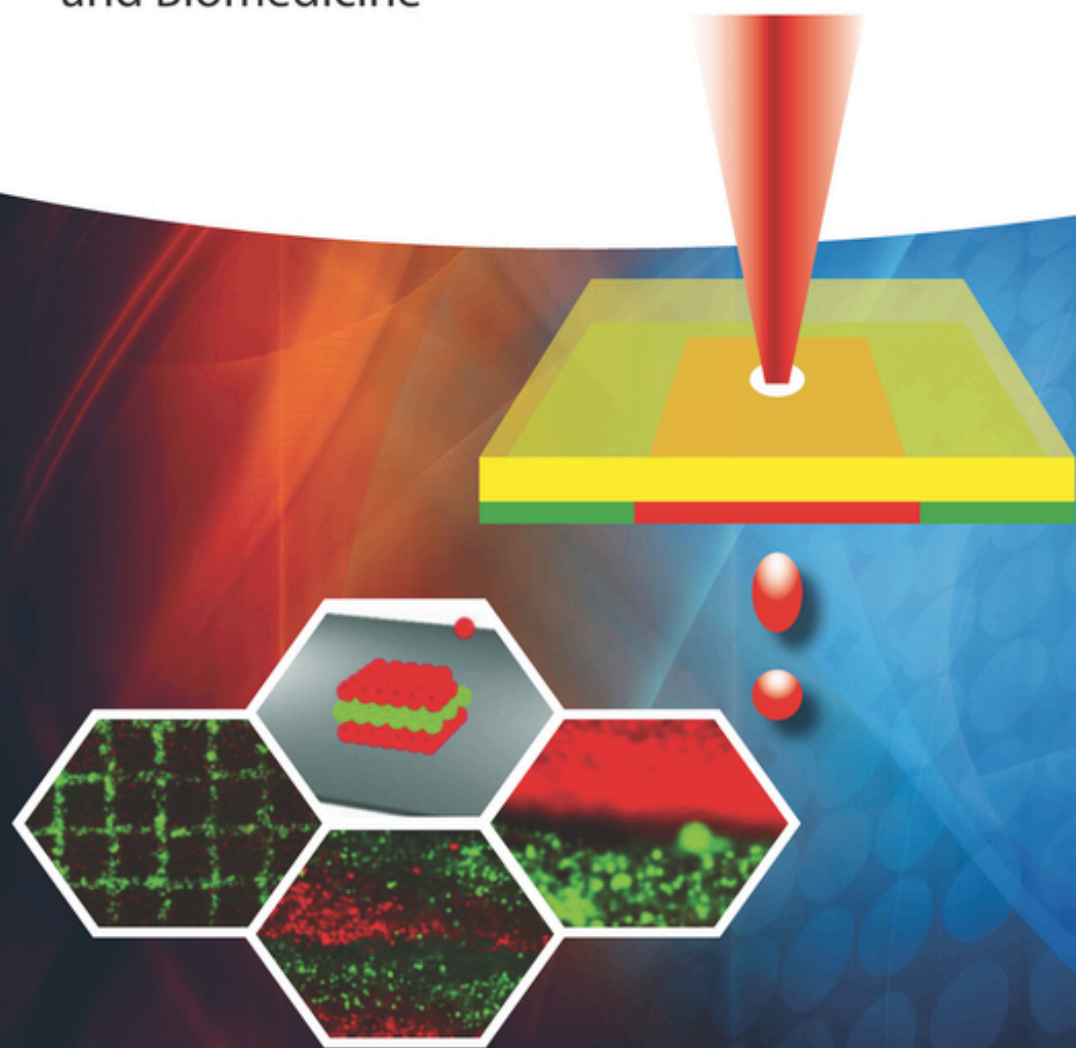


Edited by
Alberto Piqué and Pere Serra

Laser Printing of Functional Materials

3D Microfabrication, Electronics
and Biomedicine



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Contents

Preface *xv*

Part I Fundamentals 1

- 1 Introduction to Laser-Induced Transfer and Other Associated Processes 3**
Pere Serra and Alberto Piqué
 - 1.1 LIFT and Its Derivatives 3
 - 1.2 The Laser Transfer Universe 5
 - 1.3 Book Organization and Chapter Overview 8
 - 1.4 Looking Ahead 12
 - Acknowledgments 13
 - References 13

- 2 Origins of Laser-Induced Transfer Processes 17**
Christina Kryou and Ioanna Zergioti
 - 2.1 Introduction 17
 - 2.2 Early Work in Laser-Induced Transfer 17
 - 2.3 Overview of Laser-Induced Forward Transfer 19
 - 2.3.1 Transferring Metals and Other Materials with Laser-Induced Forward Transfer (LIFT) 21
 - 2.3.2 Limitations of the Basic LIFT Technique 22
 - 2.3.3 The Role of the Donor Substrate 22
 - 2.3.4 Use of a Dynamic Release Layer (DRL)-LIFT 24
 - 2.3.5 LIFT with Ultrashort Laser Pulses 25
 - 2.4 Other Laser-Based Transfer Techniques Inspired by LIFT 27
 - 2.4.1 Matrix-Assisted Pulsed Laser Evaporation-Direct Write (MAPLE-DW) Technique 27
 - 2.4.2 LIFT of Composite Matrix-Based Materials 27
 - 2.4.3 Hydrogen-Assisted LIFT 28
 - 2.4.4 Long-Pulsed LIFT 28
 - 2.4.5 Laser Molecular Implantation 29
 - 2.4.6 Laser-Induced Thermal Imaging 30

| | | |
|----------|--|-----------|
| 2.5 | Other Studies on LIFT | 31 |
| 2.6 | Conclusions | 31 |
| | References | 32 |
| 3 | LIFT Using a Dynamic Release Layer | 37 |
| | <i>Alexandra Palla Papavlu and Thomas Lippert</i> | |
| 3.1 | Introduction | 37 |
| 3.2 | Absorbing Release Layer – Triazene Polymer | 40 |
| 3.3 | Front- and Backside Ablation of the Triazene Polymer | 42 |
| 3.4 | Examples of Materials Transferred by TP-LIFT | 43 |
| 3.5 | First Demonstration of Devices: OLEDs and Sensors | 47 |
| 3.5.1 | Organic Light Emitting Diode (OLEDs) | 47 |
| 3.5.2 | Sensors | 49 |
| 3.6 | Variation of the DRL Approach: Reactive LIFT | 52 |
| 3.7 | Conclusions and Perspectives | 54 |
| | Acknowledgments | 55 |
| | Conflict of Interest | 55 |
| | References | 55 |
| 4 | Laser-Induced Forward Transfer of Fluids | 63 |
| | <i>Juan M. Fernández-Pradas, Pol Sopeña, and Pere Serra</i> | |
| 4.1 | Introduction to the LIFT of Fluids | 63 |
| 4.1.1 | Origin | 64 |
| 4.1.2 | Principle of Operation | 65 |
| 4.1.3 | Developments | 66 |
| 4.2 | Mechanisms of Fluid Ejection and Deposition | 67 |
| 4.2.1 | Jet Formation | 67 |
| 4.2.2 | Droplet Deposition | 69 |
| 4.3 | Printing Droplets through LIFT | 72 |
| 4.3.1 | Role of the Laser Parameters | 72 |
| 4.3.2 | Role of the Fluid Properties | 76 |
| 4.3.3 | Setup Parameters | 76 |
| 4.4 | Printing Lines and Patterns with LIFT | 78 |
| 4.5 | Summary | 81 |
| | Acknowledgments | 82 |
| | References | 82 |
| 5 | Advances in Blister-Actuated Laser-Induced Forward Transfer (BA-LIFT) | 91 |
| | <i>Emre Turkoz, Romain Fardel, and Craig B. Arnold</i> | |
| 5.1 | Introduction | 91 |
| 5.2 | BA-LIFT Basics | 93 |
| 5.3 | Why BA-LIFT? | 94 |
| 5.4 | Blister Formation | 97 |
| 5.4.1 | Dynamics of Blister Formation | 97 |
| 5.4.2 | Finite Element Modeling of Blister Formation | 102 |

| | | |
|----------|--|------------|
| 5.5 | Jet Formation and Expansion | 105 |
| 5.5.1 | Computational Fluid Dynamics Model | 106 |
| 5.5.2 | Effect of the Laser Energy | 108 |
| 5.5.3 | Effect of the Ink Film Properties | 111 |
| 5.6 | Application to the Transfer of Delicate Materials | 113 |
| 5.7 | Conclusions | 117 |
| | References | 117 |
| 6 | Film-Free LIFT (FF-LIFT) | 123 |
| | <i>Salvatore Surdo, Alberto Diaspro, and Martí Duocastella</i> | |
| 6.1 | Introduction | 123 |
| 6.2 | Rheological Considerations in Traditional LIFT of Liquids | 125 |
| 6.2.1 | The Challenges behind the Preparation of a Thin Liquid Film | 125 |
| 6.2.1.1 | The Role of Spontaneous Instabilities | 126 |
| 6.2.1.2 | The Role of External Instabilities | 128 |
| 6.2.2 | Technologies for Thin-Film Preparation | 129 |
| 6.2.3 | Wetting of the Receiver Substrate | 130 |
| 6.3 | Fundamentals of Film-Free LIFT | 131 |
| 6.3.1 | Cavitation-Induced Phenomena for Printing | 131 |
| 6.3.2 | Jet Formation in Film-Free LIFT | 132 |
| 6.3.3 | Differences with LIFT of Liquids | 134 |
| 6.4 | Implementation and Optical Considerations | 135 |
| 6.4.1 | Laser Source | 135 |
| 6.4.2 | Forward (Inverted) versus Backward (Upright) Systems | 136 |
| 6.4.3 | Spherical Aberration and Chromatic Dispersion | 137 |
| 6.5 | Applications | 138 |
| 6.5.1 | Film-Free LIFT for Printing Biomaterials | 139 |
| 6.5.2 | Film-Free LIFT for Micro-Optical Element Fabrication | 140 |
| 6.6 | Conclusions and Future Outlook | 141 |
| | References | 142 |

Part II The Role of the Laser–Material Interaction in LIFT 147

| | | |
|----------|--|------------|
| 7 | Laser-Induced Forward Transfer of Metals | 149 |
| | <i>David A. Willis</i> | |
| 7.1 | Introduction, Background, and Overview | 149 |
| 7.2 | Modeling, Simulation, and Experimental Studies of the Transfer Process | 151 |
| 7.2.1 | Thermal Processes: Film Heating, Removal, Transfer, and Deposition | 151 |
| 7.2.2 | Parametric Effects | 153 |
| 7.2.2.1 | Laser Fluence and Film Thickness | 154 |
| 7.2.2.2 | Donor-Film Gap Spacing | 156 |
| 7.2.2.3 | Pulse Width | 157 |

| | | |
|----------|---|------------|
| 7.2.3 | Droplet-Mode Deposition | 160 |
| 7.2.4 | Characterization of Deposited Structures: Adhesion, Composition, and Electrical Resistivity | 163 |
| 7.3 | Advanced Modeling of LIFT | 165 |
| 7.4 | Research Needs and Future Directions | 167 |
| 7.5 | Conclusions | 169 |
| | References | 170 |
| 8 | LIFT of Solid Films (Ceramics and Polymers) | 175 |
| | <i>Ben Mills, Daniel J. Heath, Matthias Feinaeugle, and Robert W. Eason</i> | |
| 8.1 | Introduction | 175 |
| 8.2 | Assisted Release Processes | 176 |
| 8.2.1 | Optimization of LIFT Transfer of Ceramics via Laser Pulse Interference | 176 |
| 8.2.1.1 | Standing-Wave Interference from Multiple Layers | 176 |
| 8.2.1.2 | Ballistic Laser-Assisted Solid Transfer (BLAST) | 177 |
| 8.2.2 | LIFT Printing of Premachined Ceramic Microdisks | 180 |
| 8.2.3 | Spatial Beam Shaping for Patterned LIFT of Polymer Films | 181 |
| 8.3 | Shadowgraphy Studies and Assisted Capture | 184 |
| 8.3.1 | Shadowgraphic Studies of the Transfer of Ceramic Thin Films | 184 |
| 8.3.2 | Application of Polymers as Compliant Receivers | 186 |
| 8.4 | Applications in Energy Harvesting | 188 |
| 8.4.1 | LIFT of Chalcogenide Thin Films | 189 |
| 8.4.2 | Fabrication of a Thermoelectric Generator on a Polymer-Coated Substrate | 190 |
| 8.5 | Laser-Induced Backward Transfer (LIBT) of Nanoimprinted Polymer | 193 |
| 8.5.1 | Unstructured Carrier Substrate | 195 |
| 8.5.2 | Structured Carrier Substrate | 195 |
| 8.6 | Conclusions | 197 |
| | Acknowledgments | 197 |
| | References | 197 |
| 9 | Laser-Induced Forward Transfer of Soft Materials | 199 |
| | <i>Zhengyi Zhang, Ruitong Xiong, and Yong Huang</i> | |
| 9.1 | Introduction | 199 |
| 9.2 | Background | 200 |
| 9.3 | Jetting Dynamics during Laser Printing of Soft Materials | 201 |
| 9.3.1 | Jet Formation Dynamics during Laser Printing of Newtonian Glycerol Solutions | 202 |
| 9.3.1.1 | Typical Jetting Regimes | 202 |
| 9.3.1.2 | Jetting Regime as Function of Fluid Properties and Laser Fluence | 204 |
| 9.3.1.3 | Jettability Phase Diagram | 206 |
| 9.3.2 | Jet Formation Dynamics during Laser Printing of Viscoelastic Alginate Solutions | 208 |
| 9.3.2.1 | Ink Coating Preparation and Design of Experiments | 208 |
| 9.3.2.2 | Typical Jetting Regimes | 209 |

| | | |
|-----------|--|------------|
| 9.3.2.3 | General Observation of the Jetting Dynamics | 212 |
| 9.3.2.4 | Effects of Laser Fluence on Jetting Dynamics | 212 |
| 9.3.2.5 | Effects of Alginate Concentration on Jetting Dynamics | 214 |
| 9.3.2.6 | Jettability Phase Diagram | 215 |
| 9.4 | Laser Printing Applications Using Optimized Printing Conditions | 218 |
| 9.5 | Conclusions and Future Work | 220 |
| | Acknowledgments | 221 |
| | References | 222 |
| 10 | Congruent LIFT with High-Viscosity Nanopastes | 227 |
| | <i>Raymond C.Y. Auyeung, Heungsoo Kim, and Alberto Piqué</i> | |
| 10.1 | Introduction | 227 |
| 10.2 | Congruent LIFT (or LDT) | 229 |
| 10.3 | Applications | 235 |
| 10.4 | Achieving Congruent Laser Transfers | 242 |
| 10.5 | Issues and Challenges | 245 |
| 10.6 | Summary | 246 |
| | Acknowledgment | 247 |
| | References | 247 |
| 11 | Laser Printing of Nanoparticles | 251 |
| | <i>Urs Zywiets, Tim Fischer, Andrey Evlyukhin, Carsten Reinhardt, and Boris Chichkov</i> | |
| 11.1 | Introduction, Setup, and Motivation | 251 |
| 11.2 | Laser-Induced Transfer | 252 |
| 11.3 | Materials for Laser Printing of Nanoparticles | 254 |
| 11.4 | Laser Printing from Bulk-Silicon and Silicon Films | 254 |
| 11.5 | Magnetic Resonances of Silicon Particles | 261 |
| 11.6 | Laser Printing from Prestructured Films | 261 |
| 11.7 | Applications: Sensing, Metasurfaces, and Additive Manufacturing | 263 |
| 11.8 | Outlook | 266 |
| | References | 266 |
| | Part III Applications | 269 |
| 12 | Laser Printing of Electronic Materials | 271 |
| | <i>Philippe Delaporte, Anne-Patricia Alloncle, and Thomas Lippert</i> | |
| 12.1 | Introduction and Context | 271 |
| 12.2 | Organic Thin-Film Transistor | 272 |
| 12.2.1 | Operation and Characteristics of OTFTs | 272 |
| 12.2.2 | Laser Printing of the Semiconductor Layer | 275 |
| 12.2.3 | Laser Printing of Dielectric Layers | 277 |
| 12.2.4 | Laser Printing of Conducting Layers | 279 |

| | | |
|-----------|--|------------|
| 12.2.5 | Single-Step Printing of Full OTFT Device | 279 |
| 12.3 | Organic Light-Emitting Diode | 281 |
| 12.4 | Passive Components | 285 |
| 12.5 | Interconnection and Heterogeneous Integration | 287 |
| 12.6 | Conclusion | 290 |
| | References | 291 |
| 13 | Laser Printing of Chemical and Biological Sensors | 299 |
| | <i>Ioanna Zergioti</i> | |
| 13.1 | Introduction | 299 |
| 13.2 | Conventional Printing Methods for the Fabrication of Chemical and Biological Sensors | 300 |
| 13.2.1 | Contact Printing Methods | 301 |
| 13.2.1.1 | Pin Printing Approach | 301 |
| 13.2.1.2 | Microcontact Printing (or Microstamping) Technique | 302 |
| 13.2.1.3 | Nanotip Printing | 303 |
| 13.2.2 | Noncontact Printing Methods | 303 |
| 13.2.2.1 | Photochemistry-Based Printing | 303 |
| 13.2.2.2 | Inkjet Printing Technique | 304 |
| 13.2.2.3 | Electrospray Deposition (ESD) | 304 |
| 13.3 | Laser-Based Printing Techniques: Introduction | 305 |
| 13.3.1 | Laser-Induced Forward Transfer | 305 |
| 13.3.2 | LIFT of Liquid Films | 307 |
| 13.4 | Applications of Direct Laser Printing | 308 |
| 13.4.1 | Biosensors | 308 |
| 13.4.1.1 | Background | 308 |
| 13.4.1.2 | Printing of Biological Materials for Biosensors | 309 |
| 13.4.2 | Chemical Sensors | 316 |
| 13.5 | Conclusions | 319 |
| | List of Abbreviations | 319 |
| | References | 320 |
| 14 | Laser Printing of Proteins and Biomaterials | 329 |
| | <i>Alexandra Palla Papavlu, Valentina Dinca, and Maria Dinescu</i> | |
| 14.1 | Introduction | 329 |
| 14.2 | LIFT of DNA in Solid and Liquid Phase | 332 |
| 14.3 | LIFT of Biomolecules | 333 |
| 14.3.1 | Streptavidin and Avidin–Biotin Complex | 333 |
| 14.3.2 | Amyloid Peptides | 337 |
| 14.3.3 | Odorant-Binding Proteins | 339 |
| 14.3.4 | Liposomes | 340 |
| 14.4 | Conclusions and Perspectives | 343 |
| | Acknowledgments | 343 |
| | Conflict of Interest | 343 |
| | References | 344 |

| | | |
|-----------|---|------------|
| 15 | Laser-Assisted Bioprinting of Cells for Tissue Engineering | 349 |
| | <i>Olivia K  rour  dan, Murielle R  my, Hugo Oliveira, Fabien Guillemot, and Rapha  l Devillard</i> | |
| 15.1 | Laser-Assisted Bioprinting of Cells | 349 |
| 15.1.1 | The History of Cell Bioprinting and Advantages of Laser-Assisted Bioprinting for Tissue Engineering | 349 |
| 15.1.2 | Technical Specifications of Laser-Assisted Bioprinting of Cells | 353 |
| 15.1.3 | Effect of Laser Process and Printing Parameters on Cell Behavior | 356 |
| 15.2 | Laser-Assisted Bioprinting for Cell Biology Studies | 358 |
| 15.2.1 | Study of Cell–Cell and Cell–Microenvironment Interactions | 358 |
| 15.2.2 | Cancer Research | 359 |
| 15.3 | Laser-Assisted Bioprinting for Tissue-Engineering Applications | 359 |
| 15.3.1 | Skin | 360 |
| 15.3.2 | Blood Vessels | 362 |
| 15.3.3 | Heart | 364 |
| 15.3.4 | Bone | 365 |
| 15.3.5 | Nervous System | 367 |
| 15.4 | Conclusion | 368 |
| | References | 369 |
| | | |
| 16 | Industrial, Large-Area, and High-Throughput LIFT/LIBT Digital Printing | 375 |
| | <i>Guido Hennig, Gerhard Hochstein, and Thomas Baldermann</i> | |
| 16.1 | Introduction | 375 |
| 16.1.1 | State of the Art in Digital Printing | 376 |
| 16.1.2 | History of Lasersonic ^{  } LIFT | 376 |
| 16.2 | Potential Markets and their Technical Demands on Lasersonic ^{  } LIFT | 377 |
| 16.2.1 | Digital Printing Market Expectations and Challenges | 377 |
| 16.2.2 | Demands on a LIFT/LIBT Printing Unit for Special Printing Markets | 378 |
| 16.3 | Lasersonic ^{  } LIFT/LIBT Printing Method | 379 |
| 16.3.1 | LIFT for Absorbing and LIBT for Transparent Inks | 379 |
| 16.4 | Optical Concept and Pulse Control of the Lasersonic ^{  } Printing Machine | 382 |
| 16.4.1 | Ultrafast Pulse Modulation at High Power Level | 382 |
| 16.4.2 | Time Schemes | 383 |
| 16.4.3 | Data Flow | 385 |
| 16.4.4 | Ultrafast Scan of the Laser Beam | 385 |
| 16.5 | The Four-Color Lasersonic ^{  } Printing Machine | 387 |
| 16.5.1 | Large-Area, High-Throughput LIFT/LIBT Inline R2R Printing System | 387 |

- 16.5.2 Printing Heads for Absorptive (Black) and for Transparent (Colored) Inks 388
- 16.5.3 Inking Units 390
- 16.5.4 Synthetic Approaches to the Absorption Layer of the LIBT Donor Surface 392
- 16.6 Print Experiments and Results 392
- 16.7 Discussion of Effects 397
- 16.7.1 LIFT Process with Continuous-Wave Laser Source and Fast Modulation 397
- 16.7.2 Special Test Pattern to Study the Transfer Behavior at High Pixel Rate 399
- 16.8 Future Directions 401
- 16.9 Summary 402
- Acknowledgments 403
- References 403

- 17 LIFT of 3D Metal Structures 405**
Ralph Pohl, Claas W. Visser, and Gert-willem Römer
- 17.1 Introduction 405
- 17.2 Basic Aspects of LIFT of Metals for 3D Structures 407
- 17.2.1 Ejection Regimes of Pure Metal Picosecond LIFT 408
- 17.2.1.1 Velocity of the Ejected Donor Material 409
- 17.2.1.2 Origin of Fragments in Cap-Ejection Regime 409
- 17.2.2 Droplet Impact and Solidification 411
- 17.3 Properties of LIFT-Printed Freestanding Metal Pillars 413
- 17.3.1 Reproducibility 414
- 17.3.2 Metallurgical Microstructure 416
- 17.3.3 Mechanical Properties 417
- 17.3.4 Electrical Properties 418
- 17.3.5 Inclined Pillars 420
- 17.4 Demonstrators and Potential Applications 420
- 17.5 Conclusions and Outlook 423
- References 423

- 18 Laser Transfer of Entire Structures and Functional Devices 427**
Alberto Piqué, Nicholas A. Charipar, Raymond C. Y. Auyeung, Scott A. Mathews, and Heungsoo Kim
- 18.1 Introduction 427
- 18.2 Early Demonstrations of LIFT of Entire Structures 428
- 18.3 Process Dynamics 431
- 18.3.1 Lase-and-Place 432
- 18.4 Laser Transfer of Intact Structures 435
- 18.4.1 Laser Transfer of Metal Foils for Electrical Interconnects 436
- 18.5 Laser Transfer of Components for Embedded Electronics 437

18.6 Outlook 438
18.7 Summary 440
 Acknowledgments 441
 References 441

Index 445

Preface

This book aims to serve as a reference on the fundamentals and applications of laser-induced forward transfer (LIFT) processes. All the chapter contributors are active members in the LIFT community, with several chapters written by some of the early adopters of the technique. Given the current attention and interest generated by additive manufacturing or AM, it is quite exciting to see LIFT being “rediscovered” given its potential as a meso- to microscale AM process. It was with this in mind that we embarked on this project with the goal of bringing together the leading LIFT researchers to share their findings in this book.

The organization of this book follows a practical approach: begin with an analysis of the LIFT process and how it has been adapted to work with almost any class of material and then discuss its broad range of applications. Our aim is not to provide an all-encompassing treatise on the subject but rather present a review of the present status of the technique with the goal of encouraging its further development, which might lead to new, not yet reported applications.

We are indebted to all the chapter authors in this book who have generously contributed their time and expertise in preparing their monographs. Most of them are old friends, while some are new members of the growing LIFT community. It has been a pleasure working with all of them in this project and we want to thank each one for their input, comments, suggestions, and support. We hope this book helps to provide a window to the intriguing phenomena of laser transfer and printing while encouraging the development of many more new and exciting applications.

Washington, DC, USA
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Part I

Fundamentals

1

Introduction to Laser-Induced Transfer and Other Associated Processes

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Digital manufacturing emerges as a new production paradigm that is transforming the future of the manufacturing industry on both the small and the large scale [1]. Despite that this new fabrication methodology is still far from being completely consolidated, there is little doubt now that the trend toward digitization is unstoppable and that almost no industrial field will remain immune to its influence in the next years. Thanks to the capabilities of the present-day computers and CAD software, as well as to unprecedented advances in serial production technologies, digital manufacturing makes possible a truly fast transition from an idea to its realization. This integrated approach provides in turn a new concept with a high degree of flexibility in that it allows to easily incorporate design changes into the final product. All these benefits have enabled digital manufacturing in such diverse industries as electronics, energy harvesting, packaging, decoration, textile manufacturing, medical instrumentation, or regenerative medicine.

Most digital manufacturing technologies are in fact “direct-writing” technologies, that is, they allow processing materials in a serial manner following a pattern previously recorded as a digital file [2]. The direct-writing approach makes patterning possible with high resolution and control in the flexible way just described. These technologies can be either subtractive, such as laser and water jet cutting, or additive, such as stereolithography and inkjet printing. Furthermore, they are sometimes assisted by other techniques that, instead of removing or adding new material, simply modify some of the properties of an already manufactured product, also in a digital way; laser sintering and laser curing are good examples of this.

1.1 LIFT and Its Derivatives

“Laser printing” is a quite general term that applies to a rather large set of additive direct-writing techniques whose principle of operation relies on a laser-induced

transfer process: a controlled amount of material is transferred from a donor system to a receiving substrate by means of laser irradiation [3]. The relative displacement of the laser beam with respect to the receiver (and eventually the donor) makes patterning possible. The most common laser printing approach is known as laser-induced forward transfer (LIFT), a technique that works according to the described principle of operation with the donor system being a thin film and the laser source usually a pulsed laser. In more detail, an optical system focuses a pulsed laser beam onto a thin film of the donor material through its supporting substrate, which needs to be transparent to the laser radiation. Under the influence of a laser pulse, a tiny portion of the donor material is ejected toward the receiving substrate as sketched in Figure 1.1, which results in the formation of a pixel/voxel on that substrate. Through the repetition of this process at different positions in the donor/receiver system, any pattern can be produced.

The donor material in LIFT can be either solid [4, 5] or liquid [6, 7]. In the earliest versions of the technique (some of which date as far back as the mid-1960s [8–10]), the donor material was always solid. In those instances, transfers took place in the gas phase with the irradiated material completely vaporized [11] or in the liquid phase if melted (totally or partially). Accordingly, deposition occurred in the receiving substrate through recondensation of the vapor in the first case and through resolidification of the molten voxel in the second [4, 5]. Those transfer modes were especially suited for the printing of metals, for which extremely high resolutions were achieved [12]. However, it was found out later that transfer from solid films was also possible in the solid state, that is, without any phase change of the donor material. In that case, transfer proceeded through the laser-induced ejection of a “flyer” that was projected away from the donor film and toward the receiving substrate, where it landed, giving way to the formation of a voxel. That transfer mechanism not only allowed printing

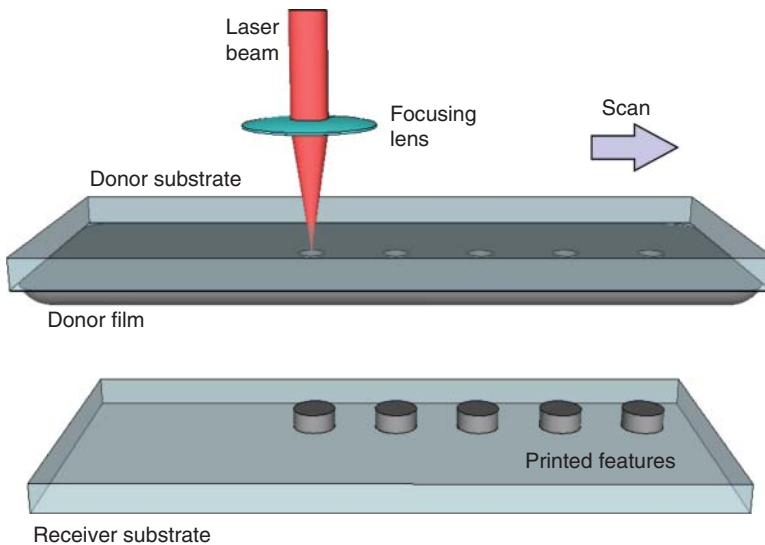


Figure 1.1 Principle of operation of the LIFT technique.

materials that would irreversibly change or decompose if melted or vaporized, such as complex ceramics [13], but also made possible to transfer stacks of different materials [14], especially interesting for the fabrication of multilayered devices. Even more than that, entire components such as surface-mounted devices and bare dies can be successfully transferred through LIFT [15].

LIFT can also work with liquid donor films. In this case, the material to print is previously dissolved or suspended in an ink that is transferred as a whole. The principle of operation of the technique is the same as with solid donor films (Figure 1.1), with the printing outcome now being a sessile droplet of the ink. Further evaporation of the ink solvents leads to the formation of the resulting pixel on the receiving substrate. The main difference with the LIFT of solids relies on the transfer mechanism: the ink is projected away from the donor film through a high-speed liquid jet that results from the expansion and collapse of a laser-induced cavitation bubble [16]. The LIFT of liquids is remarkably similar to inkjet printing regarding both transfer mechanism and printing outcome, but with significant advantages over it. Probably the most prominent is that LIFT presents fewer restrictions concerning the rheology of the printable inks: LIFT admits a substantially broader range of viscosities [17] and sizes of the particles loading the ink [18] compared to inkjet printing. Thus, such technologically interesting materials as high-solid-content inks and nanostructured materials can be successfully printed through LIFT. Furthermore, since those transfers also proceed without any significant phase change of the printed material, LIFT from liquid donor films can be used to print very sensitive materials such as biomolecules [19, 20] or living cells and tissue [21–23], which makes the technique especially suited for biosensing and tissue engineering applications.

In spite of its dominant position in the laser printing techniques universe, LIFT is not the only option to carry out laser-induced transfer. One alternative is laser-induced backward transfer (LIBT), wherein the donor film is irradiated directly, either at normal incidence through a transparent receiving substrate [2, 24] or at oblique incidence with flexible receiving substrates [25], and the irradiated material is propelled in a direction opposite to that of the incident laser beam. This approach is more restrictive and probably more difficult to set up compared to LIFT, but it has proved to be very convenient for the large-area and large-throughput printing of liquid inks [25]. Another novel departure from the traditional LIFT scheme is usually known as film-free laser printing [26]. This approach, which works only with liquid inks transparent to the laser radiation, requires the use of very short laser pulses. However, it presents the advantage of allowing to carry out transfers directly from the ink contained in a reservoir, without the need of preparing a thin film. Film-free laser printing can operate in both forward and backward configurations.

1.2 The Laser Transfer Universe

The concept of imparting kinetic energy to a solid using laser pulses can be traced back to research on the use of lasers for rocket propulsion applications

and launching of thin films to study matter under the effects of hypervelocities (>1 km/s) [27]. Early studies in the 1970s revealed that the plasma generated during the laser-induced breakdown of air near a surface would impinge on and transfer momentum to the surface [28, 29]. The use of pulsed lasers to accelerate small objects such as thin films has since then been explored to investigate means for propulsion of micro-rockets [30] and the effects of micrometeorites to simulate the effects of space debris on satellites [31–33]. These works focused on the efficiency of the release and launch process but share many similarities with LIFT.

The straight forwardness of the laser release and launch process and its relative simplicity in implementation attracted much attention in the graphics industry for digital printing tools [10]. In fact, Levene *et al.* reported in 1970 the laser-induced transfer of material across an air gap for the purposes of printing characters, recording of graphics, or marking applications [34]. The material transferred consisted of black ink from a polyethylene-backed typewriter ribbon and colored dies from a Mylar substrate across up to $100\ \mu\text{m}$ gaps using a Nd:YAG laser ($\lambda = 1.06\ \mu\text{m}$). Although the objective of this work was to develop a laser-based printing or marking process (the authors referred to it as material transfer recording), it was prescient in many ways including its reporting of not only forward but also backward transfers (called reverse transfer by the authors) and on proposing a simple physical model based on the melting and vaporization of the transferred material as a function of the laser pulse energy. Unfortunately, the authors did not apply their technique to any other types of materials, and their work went unnoticed until the late 1990s when their article began being cited within the printing and image science community. The laser forward-transfer process had to wait until 1986 to be rediscovered, this time with metals, with the work by Bohandy *et al.*, who reported on the deposition of copper metal patterns using pulses from a UV laser ($\lambda = 193\ \text{nm}$) and proposed a physical model more detailed but similar to Levene's to describe the process [4]. Furthermore, it was Bohandy's group who coined the term LIFT (for laser-induced forward transfer) to denote the process, which is essentially the subject of this book.

It was with LIFT that the use of lasers to achieve the controlled transfer of a specific material from a donor to a receiving substrate became widespread to the point that the acronym itself began to be used by some as a verb describing the process as in "LIFT-ing" a given material or ink. The success of LIFT also gave rise to numerous derivatives, all laser-based and all with their own acronym aiming at differentiating themselves from the basic technique. This book does not include all these LIFT derivatives since their discussion is beyond the scope of this volume. However, the remaining of this Introduction will provide a brief examination of some of these laser transfer techniques and include those relevant references where the reader will be able to find more details.

Early on, applications in the graphics industry motivated the use of laser transfer processes for image recording as evidenced by Levene's work. In these applications, the transfer process involves the conversion of light into heat when IR laser pulses are absorbed by IR-absorbing dye pigments dispersed in a translucent binder. Ultrafast heating of the absorbing dyes causes their decomposition, vapor generation, and thermal stresses leading to thermal ablation. These

processes known as laser ablative transfer or LAT involve delamination, rupture, and launch of the film from its carrier when the pressure of the generated gases trapped in the absorbing layer exceeds a threshold determined by the nature and thickness of the absorbing layer and laser parameters, that is, wavelength, pulse width, fluence, and so on. With LAT, it is possible to print high-resolution full-color graphics using a dry, noncontact printing process. Analysis of the LAT process was undertaken in the 1990s to determine its mechanism and optimize its operation by D. Dlott's group at the University of Illinois at Urbana Champaign. They reported various key findings including measuring heating rates and peak temperatures using dyes as molecular thermometers [35, 36] and applying ultrafast microscopy of shock waves generated with ps laser pulses [37, 38]. LAT can also be used to print nonabsorbing layers by incorporating a sacrificial laser absorbing layer first referred by Dlott's group as the dynamic release layer or DRL [39]. Finally, using a metal DRL and ps laser pulses, LAT can be achieved at low fluences ($<10 \text{ mJ/cm}^2$) by vaporizing the thin aluminum interlayer instead of the dyes, generating color images at ultrahigh speed and high resolution [40].

Another class of laser transfer techniques owe their development to the need to find alternatives for the generation of patterns, given the cost and complexity of conventional vacuum deposition and photolithography-based process. In many instances, these laser transfer derivatives were developed to address a specific class of material(s) for a given application as in the case of the organic semiconductor molecules used for organic electronic devices and organic light-emitting diodes (OLEDs). These materials present serious challenges when applied as liquid layers for large-area printing and would benefit from a dry printing process. These needs have given rise to several techniques based on laser transfer, which have met with various levels of success. One of these techniques known as laser-induced thermal imaging or LITI was originally developed at DuPont by Blanchet's group for printing conducting polymers for organic electronics [41]. In LITI, the precoated donor and receiving films are in contact and held together using vacuum. A IR cw laser is aimed through the donor film at a thin absorbing layer for conversion of the light into heat, which vaporizes an intermediate organic layer with the resulting gas implanting a third layer comprising the conductive polymer onto the receiving film. This thermal transfer method relies on release/adhesion mechanisms rather than ablation of the conductive polymer (or organic semiconductor) layers, allowing them to remain continuous rather than undergoing irreversible damage (as with ablation). LITI was further developed by the 3 M Corporation for the fabrication of LCD color filters and OLED emitters [42], and beginning in 2000, 3 M partnered with Samsung SDI to jointly develop the process for active-matrix organic light-emitting diode (AMOLED) displays [43]. The use of LITI in the fabrication of AMOLED displays, which are commonly used in smartphones, represents the most successful example to date of the commercial application of laser transfer techniques. Interesting enough, given the commercial success of LITI, other consumer product companies have developed their own versions of laser transfer technologies such as laser-induced patternwise sublimation or LIPS, which has been developed by Sony Corporation. Using LIPS, RGB pixels are patterned for OLED applications, which have been used by the Display Device

Development group at Sony Corporation to fabricate a 27.3-inch AMOLED display [44]. For heat-sensitive organic materials, LITI and LIPS might cause their damage, and the use of more efficient light-absorbing layers based on loosely connected silver nanoparticles has been investigated. This technique named nanomaterial-enabled laser transfer or NELT allows the laser printing of patterns of the OLED tris-(8-hydroxyquinoline)Al, better known as *Alq₃*, without damage [45]. These laser transfer techniques for organic electronics are highly proprietary, each being the subject of numerous patents, and require the use of multilayer, complex, and, in most cases, proprietary donor films, which has limited their use by the general LIFT community.

The implantation of intact polymer molecules using a laser transfer process has been reported by H. Fukumura's group from Tohoku University. The technique known as laser molecular implantation or LMI is used for the implantation of fluorescent molecules into polymer films at precise locations and depths [46]. In LMI, the laser passes through a transparent polymer serving as the receiving substrate, such as poly(butyl methacrylate) or PBMA, or poly(ethyl methacrylate) or PEMA, which is in contact with an absorbing polymer film containing the organic molecules to be implanted, such as pyrene [47] or photochromic molecules [48]. More recently, there have been reports on laser-implanted coumarin C545 with a process called laser-induced molecular implantation technique (LIMIT) for organic electronics and optical device applications [49]. Both LMI and LIMIT are very similar, and their use is limited to applications requiring the implantation of specific molecules on a polymer matrix just below its surface, and as such, they have not found widespread use.

As a last example of laser-mediated transfers of a material or sample, it is worth considering the process used for laser pressure catapulting or LPC. This process has been used to procure single cells or small regions comprised of homogeneous cells for subsequent molecular analysis using UV laser pulses [50]. LPC is a noncontact cell or tissue capture technique that in combination with microdissection allows the rapid preparation of samples for cell or tissue analysis. LPC can also be used for the collection of chromosomes and chromosome subfragments for gene research applications [51]. Later reports have demonstrated the use of LPC for the transfer of living cells from a microdissected cell culture, which are viable enough to be recultivated [52, 53]. The drawback of LPC is that it requires a donor film prepared by microdissection, which, given their limited size, prevents this technique from its use in transferring much larger numbers of cells as for tissue engineering applications.

1.3 Book Organization and Chapter Overview

The aim of this book is to provide an extensive overview of the topic of laser printing of functional materials. As pointed out in the preceding sections, the editors are aware that the 18 chapters of this book have not covered all the existing laser-induced transfer techniques. Instead of attempting to cover the entire field, we have preferred to focus on LIFT and its most closely related

technologies, paying special attention to their principles of operation and transfer mechanisms, without forgetting their potential and applications. In other words, we have carefully selected the most popular approaches to laser printing and aimed to provide an in-depth treatment of all of them. This book is the result of contributions by international leading experts in the field, both from the academia and from the industry, thus providing a broad perspective of the present and future of these technologies.

This book is organized into three main parts. The first one deals with the fundamentals of laser printing. In this part, the main techniques are presented and described in detail, alongside the mechanisms of transfer involved in each of them, but with no special focus on any material in particular.

In Chapter 2, by C. Kryou and I. Zergioti, the authors provide an overview of the main laser-induced transfer processes and their historical origin. This chapter serves as an introduction to the techniques that will be later analyzed in more detail, outlining their main characteristics as well as some important instrumental issues. In this chapter, the authors also introduce some of the approaches to laser printing away from the mainstream. Since these approaches are not considered in the rest of this book, by presenting them here, the authors provide the interested reader with the appropriate references for further investigation.

We devote Chapter 3, by A. Palla Papavlu and T. Lippert, to a common variation to traditional LIFT: the use of a DRL. The transfer of very sensitive materials, as well as materials transparent to the laser radiation, is usually carried out through an intermediate absorbing film. The laser pulse is absorbed within that film, which provides the donor material with the thrust required for transfer without the sensitive material being exposed to the potentially harmful laser radiation. In this chapter, the authors focus their discussion on the use of triazene polymers, by which absorption can be easily tuned to several convenient laser wavelengths and by which decomposition products upon laser irradiation are very efficient in propelling the donor material.

In Chapter 4, by J.M. Fernández-Pradas *et al.*, the authors introduce the general elements of the LIFT of fluids, probably the most widespread laser-based technique for printing inks. The authors describe the principle of operation of this particular approach to LIFT and discuss the mechanisms of liquid transfer, with their characteristic jetting dynamics. In this chapter, the authors also investigate the influence of the main process parameters on the morphology of the printed features and their correlation with the different possible transfer dynamics. Finally, the chapter considers some of the issues related with the printing of continuous patterns.

We return to the laser printing of fluids in Chapter 5, by E. Turkoz *et al.*, where the authors present another approach to LIFT with an intermediate layer: blister-actuated laser-induced forward transfer (BA-LIFT). In contrast to the strategy presented in Chapter 3, in this case, the laser-absorbing layer does not decompose completely. Upon absorption of the laser pulse, only a fraction of the relatively thick polymeric layer is ablated. The expansion of the trapped ablation products results in a blister in that layer, which provides the donor material with the required impulse for transfer. The mechanisms of liquid ejection are discussed and analyzed in detail both experimentally and through computational methods.

In Chapter 6, by S. Surdo *et al.*, the authors depart from the LIFT scheme to present film-free laser printing (or film-free LIFT), a technique that makes possible the transfer of liquids from bulk material. After discussing the problems associated with the preparation of a thin liquid film, the authors present the principle of operation of this relatively new approach and analyze in detail the mechanisms of material transfer, with a special emphasis on the differences with traditional LIFT. In this chapter, the authors also consider important instrumental aspects, as well as the different configurations through which film-free LIFT can be carried out (forward and backward). Finally, the chapter provides some examples of applications.

The second part of this book focuses on the laser–material interaction in laser printing, emphasizing those aspects that are specific to each kind of material (metals, ceramics, etc.). This part is organized according to a general materials classification.

We start this part with a complete overview of the LIFT of metals in Chapter 7, by D.A. Willis. After a general introduction highlighting the thermal nature of metal ablation, Willis reviews the main experimental and computational studies on the mechanisms of metal transfer through LIFT and the influence of the different process parameters on them. In this chapter, special attention is paid to a particular mode of deposition apparently specific to the LIFT of metals: droplet deposition. This remarkable transfer mode has allowed printing of the smallest features ever attained through laser-based processes.

In Chapter 8, by B. Mills *et al.*, the authors discuss the laser transfer of materials from solid films, an alternative particularly interesting for printing ceramics and polymers. In contrast to metals, in this case, the material is not melted, but rather transferred as a solid flyer that is propelled from the solid donor film upon absorption of the laser pulse. The authors discuss the importance of laser beam shaping in this particular approach and analyze the main issues associated with its transfer dynamics, which appears to be quite different from most of the other laser printing approaches. Although most of the chapter is devoted to LIFT, it also includes some discussion on the LIBT of nanoimprinted polymers.

Chapter 9, by Z. Zhang *et al.*, discusses LIFT of soft materials. After having introduced the LIFT of fluids in Chapter 4, the focus of attention in this chapter is aimed toward non-Newtonian fluids, with a transfer dynamics sensibly different from that analyzed in the first part of this book. The authors analyze the particular jetting behavior of these fluids, with special attention to the influence of their viscoelastic properties on the dynamics. It is remarkably interesting in this case how those viscoelastic properties make possible to build 3D structures through LIFT by means of stacking successive layers of material.

In Chapter 10, by R.C.Y. Auyeung *et al.*, the authors discuss LIFT of high-viscosity nanopastes, a particular type of inks that somehow combine some of the most relevant elements encountered in Chapters 8 and 9. On the one hand, a relatively soft material can be transferred, and on the other hand, as a congruent flyer. This approach, also known as laser decal transfer (LDT), indeed makes it possible to transfer complex geometries with a single laser pulse. Furthermore, it allows achieving conformal deposition, which makes it

especially suited for electrical contacts, for example. Similarly to the LIFT of soft materials, 3D printing through multilayer stacks is also possible.

In Chapter 11, by U. Zywiets *et al.*, the authors expand on the droplet deposition mode presented in Chapter 7 for the LIFT of metals with the aim of printing nanoparticles. In fact, the authors show that LIFT in that mode is also possible with semiconductors and demonstrate that extremely small features can indeed be obtained in that way. This chapter also explores alternatives to the traditional mode: a backward configuration for the transfer of individual nanoparticles, as well as the possibility of printing more complex patterns from prestructured films.

The last part of this book is devoted to applications. As many other digital printing techniques, laser-induced transfer can be used in a wide range of applications, some of them well consolidated in the industry and others still prospective. In this part, we present a rather comprehensive list of examples of application of laser printing and discuss the main advantages and bottlenecks of these techniques regarding their industrial implementation.

The first application that we consider is the laser printing of electronic materials, to which Chapter 12, by P. Delaporte *et al.*, is devoted. Although the chapter extensively discusses the fabrication of organic devices (thin-film transistors and light-emitting diodes), the transfer of inorganic materials (dielectrics and conductive metals, especially) is also covered. The authors present examples of successful printing of electronic materials in both solid and liquid states, as well as printing of multistack structures. In addition to the feasibility of laser-induced transfer for the fabrication of electronic devices, the chapter considers issues related to the further industrialization of the technology, such as the process speed.

In Chapter 13, by I. Zergioti, the feasibility of laser printing for producing chemical and biological sensors is explored. After an overview on the most conventional printing techniques, the authors introduce LIFT of sensing materials. The chapter reviews the different approaches of laser printing for sensor fabrication, both in the solid state and in the liquid state, and with a broad variety of materials (inorganic, organic, biomolecules, nanostructured materials), to finally provide proofs of concept of functional sensors fabricated through laser-induced transfer processes.

Strongly related with the previous chapter, in Chapter 14, by A. Palla Papavlu *et al.*, the authors consider the laser printing of proteins and biomaterials. Some of these materials can indeed be used for the fabrication of biosensors; however, there are many other interesting applications that require depositing biological materials with high resolution and control: cell growth and development studies, diagnostic tests, basic studies of biomolecule interactions, drug delivery, etc. The chapter discusses all these applications with a special focus on the particularities related with the laser-induced transfer of each type of biomolecule.

In Chapter 15, by O. K erour edan *et al.*, the authors make a step forward on the scale of biological complexity toward the laser printing of cells for tissue engineering applications. After an introduction to the subject of bioprinting, the authors focus their attention on the laser transfer of living cells and the influence

of the diverse process parameters on cell viability and behavior. In the frame of this investigation, it is especially important to provide analysis of cell–cell and cell–microenvironment interactions, issues that the chapter discusses alongside the remarkable problem of vascularization, essential for the correct development of printed tissues. Finally, the chapter reviews some studies on the laser printing of the most relevant tissues for regenerative medicine applications.

Chapter 16, by G. Hennig *et al.*, provides a complete analysis on the industrial perspectives of laser printing, with a special focus on Lasersonic[®], probably the largest printing machine based on LIFT/LIBT technologies to date. In this chapter, the authors review the state of the art of laser printing technologies in the industrial arena and discuss in all detail the main instrumental issues to be considered in the setting up of an industrial-scale printing machine. This is, in consequence, the chapter with strongest engineering focus in this book, which should serve as a bridge between the research and the development stage.

Chapter 17, by R. Pohl *et al.*, returns to the LIFT of metals, this time to carry out 3D printing. The ejection of extremely small metallic droplets described in Chapters 7 and 11 can be exploited to generate 3D structures. The process requires the fine-tuning of the laser parameters, as well as a detailed knowledge of the transfer dynamics, acquired through time-resolved imaging techniques. High-aspect-ratio freestanding pillars are generated through stacking successive melted droplets, which solidify immediately upon landing on the growing pillar. These elements constitute the building blocks that will be used later to produce more complex 3D structures.

The last chapter of this book, Chapter 18, by A. Piqué *et al.*, is devoted to the laser transfer of entire structures and functional devices. Instead of using laser printing techniques to transfer materials with the aim of manufacturing devices, in this chapter, the authors take advantage of the principle of operation of LIFT to propel entire structures and devices. The LDT technique presented in Chapter 10 can be successfully used to print interconnects in electronic circuits, for example. But the same scheme allows the transfer of small integrated devices, such as surface-mounted devices or bare dies, which can be positioned with high accuracy and control on the required positions in a more complex circuit.

1.4 Looking Ahead

As this brief introduction shows, laser transfer techniques have evolved significantly and found widespread use in many fields. Furthermore, with the advent of LIFT, these techniques have given rise to a community of practitioners who continue investigating its mechanisms and exploring its applications. This book is an attempt to document the origin and evolution of LIFT and all its variations while providing a snapshot of the broad range of present-day applications for which LIFT provides practical solutions. We cannot predict where LIFT will take us in 5 or 10 years from now, but we hope that the discussions presented by the authors of all the chapters in this book serve to lay the groundwork for the next generation of LIFT-based techniques and their new applications.