DfX in Action: Modular Strategies for Assembling, Servicing, and Optimizing Complex Optical Systems

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ABSTRACT

Design for Excellence (DFX) is a strategic approach that guides key decisions throughout the design process of complex optical systems. The "X" can represent various processes within manufacturing, assembly, cost, or performance. Explore how modular design techniques support assembly, serviceability, and system performance, offering real-world insights into practical implementation, design trade-offs, and system optimization. Applying DFX principles and modular techniques early in development can streamline processes, reduce costs, and elevate overall product quality.

Keywords: DFX, modular design, assembly, manufacturing, performance, development

1. INTRODUCTION

In the design of optical systems, achieving all desired product needs such as high performance, cost reduction, and long-term reliability is a complex challenge. Design for Excellence (DFX) offers a strategic approach to address this by integrating key considerations, such as manufacturability, assembly, and cost directly into the design process. Rather than a one-size-fits-all method, the "X" in DFX can be tailored to specific design objectives or a blend of a few objectives. Some examples of DFX are Design for Manufacturing (DFM), which ensures components are optimized for scalable production. Design for Assembly (DFA), which reduces complexity and assembly time. Design for Cost (DFC), which aligns design decisions with budget constraints, and Design for Serviceability (DFS) which supports long-term maintainability. When applied effectively, DFX can help guide development efforts while maximizing the most important product outcomes. This paper explores an example of an optical system where DFX is applied to the early system architecture design choices. Two different outcomes will be discussed, one with the objective of DFM, and the other, DFA.

2. THE EXAMPLE OPTICAL SYSTEM

Consider the typical fluorescence detection system illustrated in Figure 1, where two primary optical paths are combined to enable sensitive fluorescence imaging. The illumination path projects excitation light onto the sample plane, exciting fluorescent molecules within the specimen. The imaging path then collects the emitted fluorescent light from the sample and maps it onto a detector.[1] This high-level system architecture forms the foundation upon which DFX principles can be applied.

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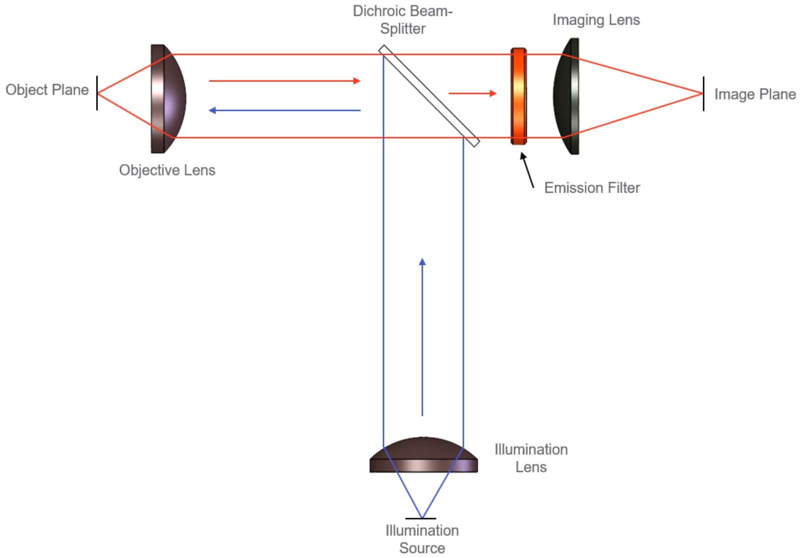

Figure 1. High-level optical architecture of a fluorescence imaging system. Excitation light (illumination source) is directed towards the dichroic beam-splitter, where it is delivered to the object plane through the objective lens. Emission light is collected by the objective lens, passes through the emission filter, and is imaged onto the image plane by the imaging lens.

The fluorescence detection process relies on the interaction between the excitation light and the sample, which induces emission at longer wavelengths. This emission light can be separated from the excitation light using a dichroic beam-splitter. Additionally, an emission filter is typically included to further refine the spectral region of interest. This filter ensures that only the desired fluorescent signal reaches the detector, minimizing background noise and improving the signal-to-noise ratio.[2] While the system is depicted with single elements representing the objective lens and imaging lens for clarity, real fluorescence imaging systems may utilize far more complex optical assemblies. The objective lens could be a complex, high NA objective lens, and the imaging lens might be composed of two or three elements to produce a well-corrected image onto the detector. Each of these optical components must be carefully designed and integrated, with attention to tolerances and alignment. DFX methodologies can help manage the early design choices to ensure the final system not only performs but also has the key features of the desired DFX approach.

3. METHODOLOGY BEHIND DFX

Selecting the appropriate DFX path for optical systems is a critical early step in the development process and is one that must be approached from a system or product-level perspective. Optical systems are inherently multidisciplinary. In addition to the optical elements, they are frequently combined with mechanics, electronics, and software to function properly. Optimizing one element or area of the design in isolation can lead to trade-offs or challenges elsewhere. For example, improving optical performance through tighter tolerances might inadvertently increase manufacturing complexity and cost. Therefore, the DFX process should begin by understanding the entire system context. This includes many requirements such as the end-user applications, the operational environments, product lifetime, and business constraints.

The DFX process begins with gathering and identifying the key product needs. The first step is to map the product or system-level needs to the appropriate DFX principle. Since it is rarely feasible to optimize every aspect of the design equally, a process of rank-ordering is used to prioritize the DFX paths. Table 1 shows a highly simplified matrix that can allow development teams to visually see each design need and evaluate which DFX focus areas contribute most to the system's success. This ensures that resources are allocated where they will have the greatest impact, and it helps manage trade-offs effectively. For example, if performance and reliability are critical, while cost is a lower priority, the development team may tolerate more expensive components to achieve tighter control critical tolerances.

Customer Need	DFX Principle	Design Implementation Examples
High optical performance	Design for Performance (DFP)	Minimize aberrations, ensure high resolution or throughput, and add compensators to recover performance
Low manufacturing cost	Design for Manufacturability (DFM), Cost (DFC)	Use standard optics, design components for use in multiple areas, relax tolerances, and reduce part count
High reliability	Design for Reliability (DFR)	Shock/vibration-proof, thermally stable design
Prototyping	Design for Assembly (DFA), Modularity	Simplified assembly, modular design
Ease of service/upgrade	Design for Serviceability (DFS)	Access to components that require frequent service, highly modular components

Table 1. DFX matrix with examples of desired customer needs, their mapped DFX principle, and some design implication details. Customer needs can be rank-ordered to determine the most important design areas.

Ultimately, the selection of the DFX path should be iterative and collaborative, involving cross-functional input from optical, mechanical, electrical, and manufacturing teams. Taking a system-level approach ensures that the optical design not only functions as intended but is also aligned with the customer and business needs.

4. SCENARIO 1: DESIGN FOR MANUFACTURING

Design for Manufacturing (DFM) can be an important consideration in the development of a fluorescence detection system. Given the broad requirements when developing such optical systems, a system-level DFM approach is essential to balance performance, cost, and manufacturability. The alignment, tolerance management, and component integration must be addressed early in the design process.

One of the key elements in a fluorescence system is optical tolerance management. Both the objective and imaging lenses may require tight alignment to maintain acceptable performance, especially when capturing weak fluorescence signals. However, not all components need ultra-tight tolerances. Applying DFM in this case may warrant redesigning the optical architecture to eliminate any potential downstream manufacturing difficulty. Let’s assume that the optical design is not completed yet and the designer is able to get input from the opto-mechanical team. They may discover that maintaining centration alignments of a few microns, which may work great from an optical standpoint, creates sufficient difficulty for the mechanical team. Early collaboration between cross-functional teams can help prevent any one team or discipline from experiencing this difficulty. This enables cost-effective production without degrading optical quality. Consider the objective lens interface shown in Figure 2. Here, the interface is not the typical threaded variety found on commercial objectives. A piloted flange is incorporated to achieve both control over angular tolerances and centration tolerances of the completed objective lens assembly. With this approach, the optical engineers and the mechanical engineers can settle on an as-build uncertainty of less than 0.0005” [12.7um] in centration and less than 0.02 degrees of tilt. Applying these inputs to the optical tolerance model will help inform design choices and aid in creating a robust solution.

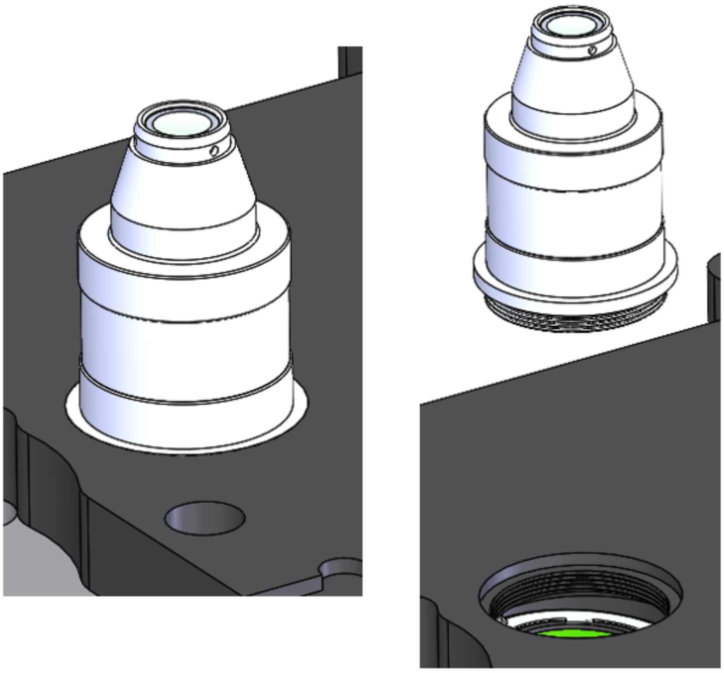

Figure 2. A microscope objective interface with a pilot flange that interfaces with a precision bore to establish centration and angularity. [Courtesy of Optikos Corporation]

The dichroic beam-splitter has its own set of manufacturing and assembly constraints. Its angular placement can be critical, and the mounting structure must allow precise positioning without inducing stress or misalignment. Designing self-aligning mechanical features, such as reference surfaces or kinematic interfaces, can reduce assembly time and improve positional uncertainty. Figure 3 illustrates an emission filter mount where reference surfaces locate the filter, and a twist-lock style retainer secures it in place. The housing that accepts the emission filter is injection molded, aiding in a low-cost solution. A closer look shows some other key elements of DFM. The retainer is made from flat stainless steel and is produced by a photo etching process. There is no forming needed for this part, and, in high quantities, its cost is much less than that of a standard threaded retainer. Once installed, the three inner tabs contact the filter ring while the outer tabs interface with the housing. Since the inner and outer tabs are rotationally offset, a natural flexure or wave is formed and provides the spring retention force. The filter used here is off-the-shelf, eliminating the need for coating development time and can be affordably procured. Lastly, there are no fasteners used and during the assembly process a specialized tool is used to quickly insert and lock the retainers in place.[3]

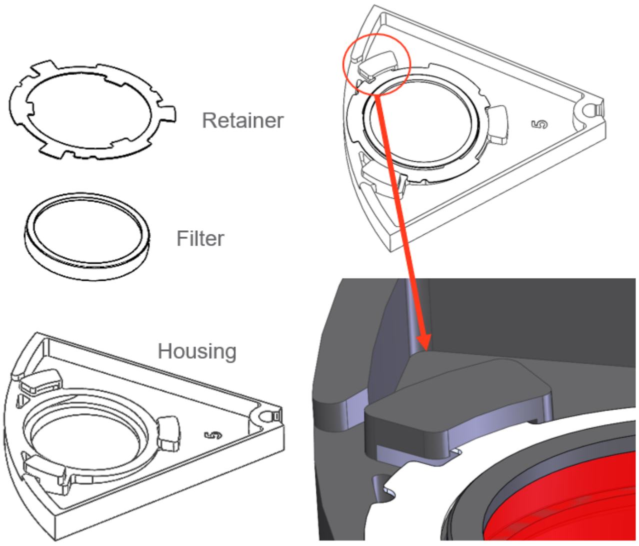

Figure 3. Filter mounting design that features and injection molded housing, an off-the-shelf ring mounted filter and a photoetched flat stainless steel retaining ring (Left). Detail view of the retainer tab retention feature on the molded plastic housing (Right). [Courtesy of Optikos Corporation]

The illumination path, which can be less sensitive to alignments, may benefit from molded plastic optics, provided the optical power and thermal load are low. Throughout the system, designing for ease of assembly, alignment, and minimizing the number of adjustable degrees of freedom helps ensure that the system can be manufactured at scale while maintaining the optical integrity required. An example for consideration is the alignment of the illumination path. When analyzing the optical system, there are many elements that are in the illumination path that require tolerancing and management. A common approach is to align each individual component as the system is assembled, which works, but DFM can offer some alternate methods. Instead of aligning each component, it may be possible to push all the alignment tolerances to one single component. In the case of the illumination path, the illumination source can be positioned in the X and Y axes to spatially steer the output light. Moving the illumination source in the z-axis achieves focus. The DFM approach with this configuration would be to establish the as-built mechanical tolerances from the dichroic beam-combiner and the lenses, and analyze performance recovery by moving the source in x, y, and z. A hidden benefit with respect to DFM here is that the illumination source is located in a very accessible area, allowing for ease of attaching external fixturing during the assembly process. Figure 4 shows the output effect of translating the illumination source, rays are drawn highly skewed for clarity.

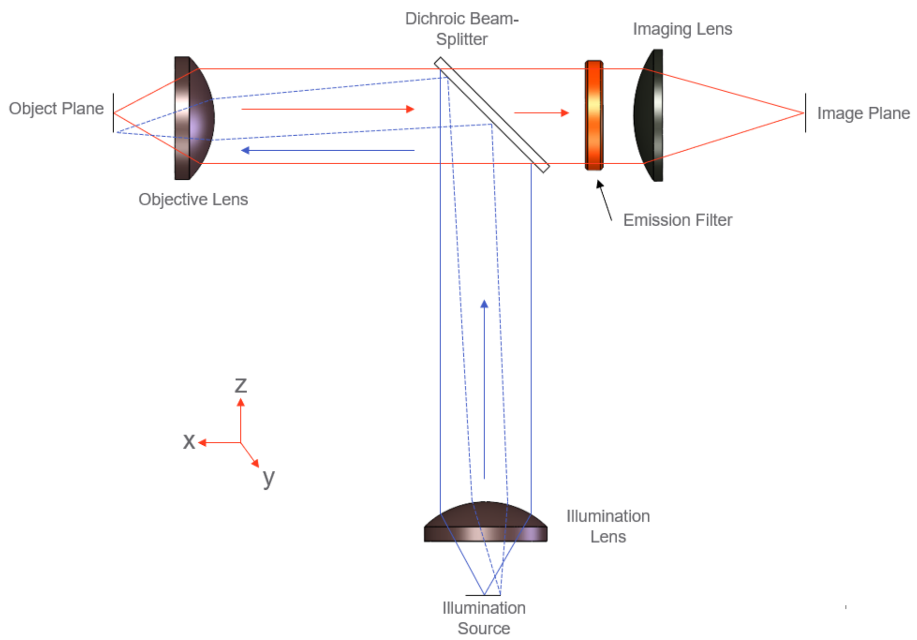

Figure 4. Translated ray paths (greatly exaggerated) to show the relationship between source displacement and object plane location. The illumination source can be fixtured and manipulated in a way to accomplish the alignment needs while hard mounting all other components.

5. SCENARIO 2: DESIGN FOR ASSEMBLY AND DESIGN FOR MODULARITY

Design for Assembly (DFA) and Design for Modularity can play an important role in the development of a prototype when the final product configuration is still uncertain. Fluorescence-based optical systems can benefit greatly from modular, easy-to-assemble parts that simplify testing and evaluation. By breaking the system into discrete, self-contained modules, the development team can quickly iterate on individual sections without needing to rebuild the entire system. This helps accelerate development times and improve evaluation flexibility.[4]

A fundamental aspect of DFA in this context is the incorporation of self-aligning features and datum-controlled interfaces within each module. Precise alignment of the dichroic beam-splitter, objective lens, and imaging lens can be essential to maintain performance. Using precision-machined reference surfaces or kinematic mounts within modular units allows the ability to install and replace components accurately without extensive adjustment. This modular strategy facilitates repeatable assembly and can be a key feature in prototyping efforts. Figure 5 illustrates a dichroic beam-splitter module. The dichroic is installed in a carrier that inserts into the structure of the optical system. There are a few key features, first, the dichroic beam-spliter is registered against a reference surface, which in turn has prescribed tolerances to its interface features on the system structure. Second, the structure has mating pins that ensure the positioning of the beam-splitter is well-controlled and repeatable. If, during the prototyping phase, a new dichroic is to be tested, then simply swapping out the modules is all that is needed, with no further alignment required.

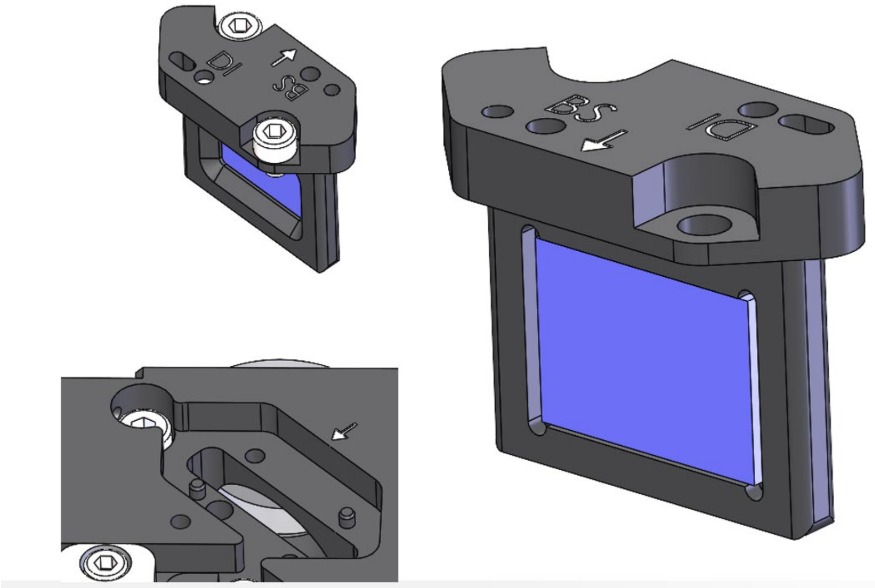

Figure 5. Views of a modular dichroic beam-splitter mount showing optic mounting references and pin/slot mechanical interface. Note the inclusion of a lock-out pin feature next to the alignment pins in the system structure. [Courtesy of Optikos Corporation]

Furthermore, the physical layout and assembly sequence should prioritize easy access and rapid interchangeability of key optical components. Design provisions for testing and beam access allow tools to be inserted along the optical paths without full disassembly. An additional consideration, particularly useful for prototyping, is the inclusion of extra space or areas where components can be added in the future. Since prototyping has some degree of uncertainty, adding these extra features can reduce the redesign time and speed up the evaluation efforts. Figure 6 shows the inclusion of an additional illumination channel. By adding in the features to accept these additional components, the optical system can be built up with the basic layout, and then the additional components can be easily added later. Taking DFA further here can be shown in Figure 7 where the same cartridge is used for the second illumination beam-combiner and then shown implemented for multiple channels. The labeling helps identify which optic is installed, and the lock-out pin mentioned earlier eliminates the possibility of installing a cartridge in the incorrect position.

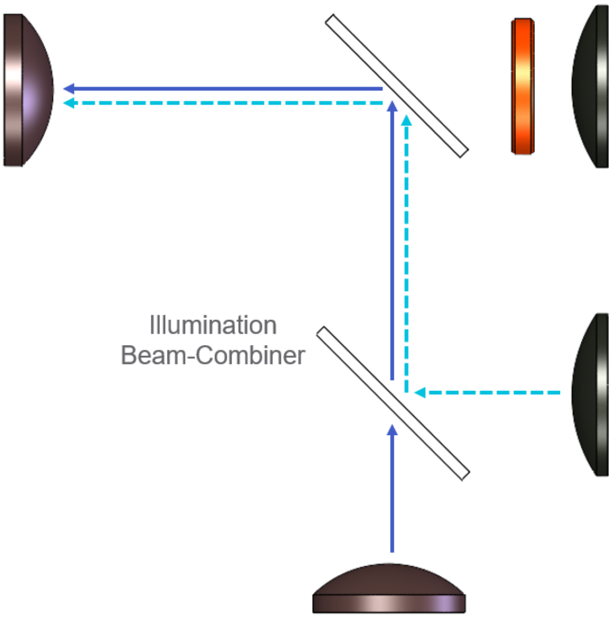

Figure 6. Additional components added to the fluorescence imaging system, where a second illumination channel is shown with the light path highlighted with dashed arrows.

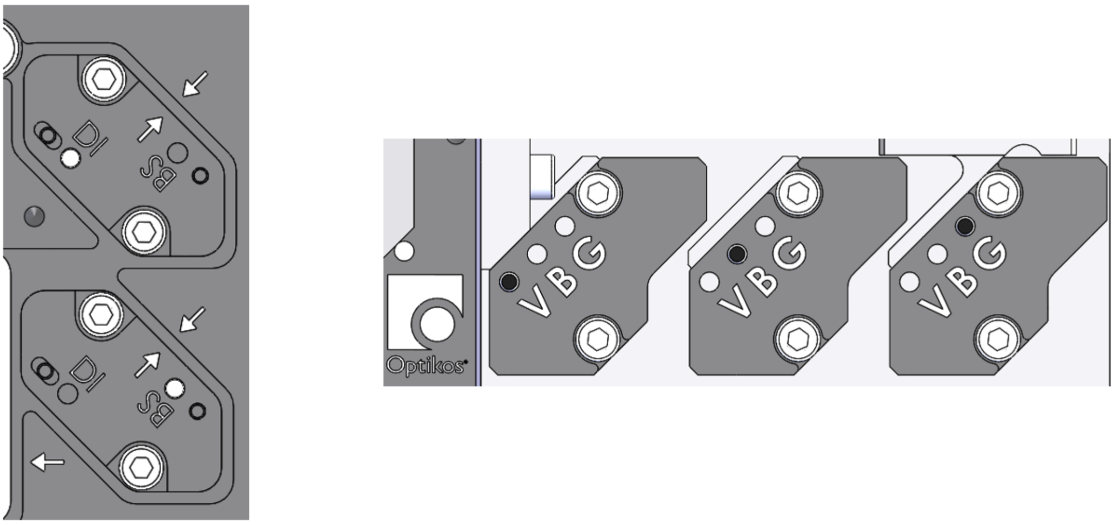

Figure 7. Two instantiations of the modular beam-combiner mount are shown. The dichroic beam-splitter and illumination beam-combiner (Left) and three illumination combiners for various wavelengths, violet, blue, and green (Right). [Courtesy of Optikos Corporation]

6. COMPARISON OF THE TWO SCENARIOS

When designing an optical system, incorporating the principles of DFX allows for a comprehensive approach that optimizes the system for specific customer needs. Each method discussed addresses a different phase of the product's development and use, but together they contribute to a system that is not only high performing but also scalable and cost-effective. Table 2 shows a comparison between Design for Manufacture and Design for Assembly/Modularity.

	DFM	**DFA/Modularity**
Primary Goal	Reduce manufacturing cost and complexity	Simplify and streamline the assembly process
Key Benefits	Lower production cost, better yield	Faster assembly, fewer errors, repeatability
Targeted Area	Component fabrication	System assembly
Design Emphasis	Tolerance control, standardization, and material choice	Alignment features, part reduction, and logical sequence

Table 2. Summary comparison table with key features and the related design aspects for either Design for Manufacturing (DFM) or Design for Assembly (DFA).

DFM ensures that the optical and mechanical components of the system, such as the objective lens, imaging lens, and dichroic beam-combiner, can be produced efficiently and assembled reliably. This involves selecting standard, readily available optical parts and materials, avoiding over-specification of tolerances, and designing components that align with common manufacturing processes like molding or standard machining.[5] DFA, particularly when applied to prototypes, focuses on simplifying how these components come together during assembly. DFA emphasizes features like modularity and intuitive assembly sequences. DFM and DFA each serve unique but complementary roles in the development of an optical system.

7. CONCLUSION

Applying DFX principles is important in optical product development because it encourages a comprehensive, system-level approach that considers nearly all aspects of the product requirements. Optical designs often demand extremely tight tolerances and can become very challenging when it comes time to implementing a mechanical design. Without careful attention to manufacturability, assembly, serviceability, and other key factors, even the most innovative optical designs can face significant challenges during production or even fail to meet performance expectations. By incorporating DFX early on, development teams can identify potential issues, reduce complexity, and optimize within their engineering domain. This helps prevent costly rework, shortens time to market, and ensures consistent quality. Ultimately, embracing DFX principles turns complex optical systems into robust commercially viable solutions that provide lasting value to customers.

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