Integrated Optical Systems for Excitation Delivery and Broadband Detection in Micro-fluidic Electrochromatography

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ABSTRACT

We have designed and assembled two generations of integrated micro-optical systems that deliver pump light and detect broadband laser-induced fluorescence in micro-fluidic chemical separation systems employing electrochromatography. The goal is to maintain the sensitivity attainable with larger, tabletop machines while decreasing package size and increasing throughput (by decreasing the required chemical volume). One type of micro-optical system uses vertical-cavity surface-emitting lasers (VCSELs) as the excitation source. Light from the VCSELs is relayed with four-level surface relief diffractive optical elements (DOEs) and delivered to the chemical volume through substrate-mode propagation. Indirect fluorescence from dye-quenched chemical species is collected and collimated with a high numerical aperture DOE. A filter blocks the excitation wavelength, and the resulting signal is detected as the chemical separation proceeds. Variations of this original design include changing the combination of reflective and transmissive DOEs and optimizing the high numerical aperture DOE with a rotationally symmetric iterative discrete on-axis algorithm. We will discuss the results of these implemented optimizations.

1. INTRODUCTION

Two generations of an integrated microsystem that delivers pump light and collects the laser-induced fluorescence for electrochromatography will be presented. Electrochromatography, also known as capillary electrophoresis, is an analytical process that separates, in time, chemical components within a fluid. Liquid flow is generated by applying a potential along the liquid capillary, driving charged molecules along the defined capillary and separating species according to their charge-to-mass ratio. This electro-osmotic flow results in a planar liquid front surface, as opposed to the parabolic liquid front surface obtained in pressure driven flow (where the velocity is zero on the walls), and thus does not distort the order of the separated chemical components as the sample progresses. At the end of the separating channel, the various chemical components may be identified through laser induced fluorescence. In the sensors described here, indirect fluorescence is utilized where the presence of components to be identified quenches dye fluorescence within the liquid. The time-varying fluorescent signal is collected and analyzed for target molecule detection and concentration. This program seeks to reduce, what is typically a slow and unwieldy bench top analytical laboratory instrument, to a hand-held, portable device that can rapidly detect and analyze a liquid sample. This is accomplished by miniaturizing and integrating components and subsystems into one multichip microsystem. This microsystem combines, onto a single multichip module, liquid sample manipulation and separation, optical source, excitation delivery optics, fluorescence collection optics, and signal detection.

Many advantages of scaling down a bench-top device to a hand-held module are readily apparent. An integrated microsystem saves space, weighs less, and can be more mechanically robust than its larger counterpart. These improvements are mandatory if the analytical instrument is to be portable. Moreover, miniaturized fluidics necessitate smaller sample volumes, result in quicker separation times, and employ lower supply voltages to obtain equivalent fields for the electro-osmotic flow.

The increasing availability of very small, inexpensive, low power-dissipating laser sources in a wide range of applicable wavelength is also a driver in microsystems technology. The high-quality optical beam and possible two-dimensional array format of vertical cavity surface emitting lasers¹ (VCSELs) make them ideal optical sources as well as packaging solutions.

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The micro-optical regime may be addressed with diffractive optical elements (DOEs) which, with a binary optics approach, take full advantage of well-established lithographic processes. Finally, as element critical dimensions decrease so that feature sizes are on the order of a wavelength or less, the physical optics domain may be accessed and subwavelength devices such as effective index elements, polarizers, and waveplates are possible²⁻⁴.

Integrated microsystem design and fabrication challenges include efficient realization of high numerical aperture optics, application of DOEs for broadband fluorescence collection, effective separation of excitation light from fluorescence for optimum signal-to-noise, and development of surface mounting techniques for electronic/optical hybrid assembly.

2. DESIGN, FABRICATION AND ASSEMBLY

Figure 1 depicts the optical layout and chemical separation channel in the first generation μ ChemLab chemical detection and analysis series. Figure 2 shows the optical substrate as fabricated. One 750 nm VCSEL in the 2X2 array is chosen as the excitation source and is flip-chip bonded to a small, fused silica substrate, which is attached to the larger fused silica substrate via an adhesive frame. The optical pump beam is delivered to the chemical separation channel through substrate mode propagation. The first optical element for the excitation source is a four level, 0.9 mm diameter, reflective DOE (on the bottom of the transparent substrate) that both deflects at 45 degrees and images the VCSEL emission onto the separation channel. Two simple gold mirrors ensure pump beam reflection at the top and bottom of the substrate before the chemical channel is illuminated. The resulting laser-induced fluorescence is collected and collimated by a fast (F/1) reflective, annular DOE. This large, on-axis DOE has a diameter of 2 mm and is also implemented in four levels. An interference filter, before the detector, blocks any pump light from the collected fluorescence signal of interest. The compact micro-optical system spans 6 mm on the substrate (from VCSEL center to detector center).

Figure 1 Optical substrate layout for the first generation μ ChemLab microsystem.

Figure 2 Photograph of the transparent optical substrate for the first generation μ ChemLab with off-axis DOE, two mirrors (one on top and one on the bottom of the substrate), and the annular DOE.

The combined optical/chemical channel substrate in the first generation of μ ChemLab ensures alignment of these two subsystems as part of the fabrication process, so that only the VCSEL subsystem requires alignment during assembly. However, the second generation μ ChemLab design physically decouples these two functions so that the complete system yield might improve. Figure 3 shows the cross-section layout of the optical substrate and the chemical separation channel substrate below it for the second generation μ ChemLab.

Figure 3 Cross-section layout of the optical substrate and chemical separation channel substrate for the second generation μ ChemLab.

In addition to separating the optical substrate from the chemical channel substrate, the second generation μ ChemLab design implements transmissive DOEs, rather than reflective. The first 0.35 mm diameter DOE is again an off-axis element that deflects the light at a reduced angle of 26 degrees and images the VCSEL emission onto the chemical separation channel. Two simple mirrors keep the beam in substrate mode propagation. In this design, the fluorescence signal is collected and collimated by an aggressive, F/0.64, four level, 2.8 mm diameter transmissive DOE. This collection optic was implemented both as a standard Fresnel zone lens and also as an optimized four level DOE that maximizes fluorescence collection. Details of the design and performance comparisons are in the next section. The final optical system span of 3.5 mm, from VCSEL

center to detector center, is significantly more compact than that of the first generation μ ChemLab. Figure 4 is a photograph of this second generation μ ChemLab optical substrate.

Figure 4 Photograph of the transparent optical substrate for the second generation μ ChemLab with off-axis DOE, two mirrors (one large and out of focus on bottom, and one small on the top of the substrate), and the large on-axis DOE.

Figure 5 is the 2X2 VCSEL array that is flip chip bonded⁵ onto a small fused silica substrate in the second generation μ ChemLab prototype. This tiny coupon is then adhesively attached to a ceramic frame (as in Figure 6) which contains more robust pads for electrical connections to the rest of the instrument. The ceramic frame provides the precise spacing between the VCSEL and the first DOE (in air) so that the contrast in refractive indices at the DOE surface is optimal. The ceramic frame subassembly mounts to the optical substrate as shown in Figure 6. Finally, this optical assembly is mounted to the chemical channel substrate, Figure 7, whose fluidic properties have been characterized in a parallel process.

Figure 5 VCSEL array which is flip-chip bonded to the small transparent fused silica substrate.

Figure 6 Optical subsystem consisting of: VCSEL array on small, transparent fused silica substrate, mounted on ceramic substrate with electrical pads, all mounted on the transparent, fused silica optical substrate containing mirrors and DOEs.

Figure 7 Two optical subsystems mounted on the transparent chemical channel substrate for separations.

3. RESULTS

When possible, individual components and subassemblies of the described microsystems are characterized before and after integration, as part of the assembly process. For example, in the second generation μ ChemLab the fluidics substrate is flow tested and leak checked before it is combined with the optical substrate. Results from the first generation μ ChemLab tests include an overall efficiency of 37% for the excitation portion of the optical system. Signal to noise experiments were carried out for the complete first generation μ ChemLab microsystem which demonstrated a 100:1 ratio when measuring the

fluorescent signal from a 10^{-4} M solution of CY-7 dye. These details have been previously presented and published⁶⁻⁸. On the other hand, both versions of the collection optic in the second generation μ ChemLab have only recently been realized and characterized, and the results are described here.

The collection DOE for the second generation μ ChemLab configuration was implemented as a standard transmissive Fresnel zone lens in four levels. Scalar theory predicts the efficiency for this lens at 81.6%. However, scalar theory is not sufficient for this fast lens ($F/0.64$), with a minimum feature size of $0.2\ \mu\text{m}$. We can more rigorously estimate the efficiency of such a lens using an approach introduced by Swanson⁹ where the lens is divided into equal area rings. An efficiency, using rigorous coupled wave analysis on each ring, is obtained from a representative period per ring. The results from this procedure are shown in Figure 8 where the theoretical efficiency for an $F/0.64$ lens is 62%. For this graph, the measured and theoretical efficiencies are defined as the amount of light in the -1^{st} order divided by the total transmitted light, modeling an anti-reflection coated optic with no loss. As expected, the theoretical efficiency approaches the scalar prediction as the lens $F/\#$ increases.

Figure 8 DOE efficiency rigorous, theoretical predictions (squares), and measured efficiencies for the standard Fresnel zone lens (triangle), and the optimized lens (diamond).

The measured efficiency for the standard $F/0.64$ Fresnel zone lens is 42% (see Figure 8). Here, tight mask alignment tolerances and fabrication limitations combine to reduce optimal theoretical efficiency. This lens was designed by initially identifying an appropriate continuous phase profile, then digitizing to four levels, and finally adjusting this binary lens profile to fulfill the minimum feature size restrictions and snap to the allowable grid. Thus the implemented phase profile is not precisely the initial design.

While these fine adjustments are not likely to affect large $F/\#$ lenses, they can be significant with our $F/0.64$ collection optic. For this reason, the four level, transmissive collection optic for the second generation μ ChemLab was redesigned using an optimization routine called RSIDO (Radially Symmetric Iterative Discrete On-axis) encoding¹⁰. This method constrains the binary phase profile to remain within the fabrication limits of feature size and placement. Thus only realizable lens designs are considered.

The optimization method utilizes simulated annealing¹¹. In our case, the merit function was a maximum irradiance within a given target area. Since this is also an objective that a Fresnel zone lens may satisfy, the optimized and standard final designs are similar. In general, the optimized phase profile departs from that of the standard design near the edge of the lens where the spatial frequency is highest. Here, the feature sizes do not necessarily monotonically decrease as can be seen in the designed phase profile near the lens edge of Figure 9. The result is that the measured efficiency, 51%, for the full $F/0.64$ optimized lens is superior to that of the standard Fresnel zone lens as illustrated in Figure 8. Note that the measured

performance of the two lenses are comparable as the $F/\#$ increases (as the illuminating aperture decreases) implying that the primary difference in the phase profiles was near the lens edges.

Figure 9 Optimized DOE profile at the edge of the lens.

Both lens designs (and the more rigorous theoretical predictions) assume a uniform illumination of the DOE. However, irradiance profiles of the beam in the configuration for the efficiency measurements demonstrate that the beam irradiance cross-section is gaussian for the large aperture lenses (see Figure 10). This lack of light near the lens edges may explain why the large aperture (i.e., $F/0.64$) efficiency measurements are lower than the theoretical values predicted for uniform illumination. When the apertures are reduced so that the larger $F/\#$ measurements can be obtained, the irradiance profile approaches a uniform one, and the corresponding efficiency measurements approach the theoretical values.

Figure 10 Irradiance profiles for the input beam to the DOEs for the low $F/\#$ (left), and high $F/\#$ (right) measurements.

Lastly, the fully integrated second generation μ ChemLab is to detect, through indirect fluorescence, the presence of explosives and related degradation products. The goal is to separate and identify these components in a few minutes. Figure 11 is a complete second generation μ ChemLab separation which indicates the presence of nine of these chemical constituents (at a concentration of 50 ppm for each explosive) in under a minute¹².

Figure 11 Indirect, laser-induced detection of explosives on the second generation μ ChemLab.

4. CONCLUSIONS

We have described two generations of a highly compact optical system that delivers excitation light and collects laser-induced fluorescence in a fluidic chemical separation system employing electrochromatography. We presented initial designs, fabrication criteria, individual component performance as well as a chemical separation result for the complete μ ChemLab microsystem, with special emphasis upon the optical subsystem. Both generations of μ ChemLab utilized four-level DOEs to relay, through substrate mode propagation, the emission from a VCSEL to the chemical separation channel, and to collect the resulting fluorescence. The first generation μ ChemLab contained reflective DOEs for both pump delivery and fluorescence collection. Signal to noise for this free space system, with a fast F/1 collection DOE, was measured at better than 100:1. The second generation μ ChemLab optical design was more compact with an even faster, F/0.64, transmissive diffractive collection optic. This component was implemented as a standard Fresnel zone lens with measured efficiency of 42%, and as an optimized diffractive optic with measured efficiency of 51%. These values compare well with the theoretical predicted efficiency of 62% from a rigorous coupled wave analysis approach. Finally, the results from a separation of nine explosives and related degradation products were obtained in less than a minute with the complete μ ChemLab microsystem.

ACKNOWLEDGEMENTS

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

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