On-chip Optofluidic Grating Spectrograph for Biomedical Applications

Conference Paper *in* Proceedings of SPIE - The International Society for Optical Engineering · October 2013

DOI: 10.1117/12.2024601

Zhenyu Li
George Washington University

On-chip Optofluidic Grating Spectrograph for Biomedical Applications

Zhenyu Li
Department of Electrical and Computer Engineering, The George Washington University, Washington DC 20052, US
zhenyu@gwu.edu

ABSTRACT

This paper presents a liquid metal based on-chip optofluidic grating spectrograph integrated with polydimethylsiloxane (PDMS) microfluidics for biomedical applications such as handheld fluorescence-actuated cell sorting, fluorescence immunosensing and Raman spectroscopy. We designed a Czerny-Turner spectrograph with 1.4nm spectral resolution, 300nm *FSR* and a footprint of 1cm by 2cm. The planar spectrograph structure was fabricated in PDMS using conventional replica molding soft lithography, and then filled with room temperature liquid metal, Gallium-Indium-Tin Alloy. The material and fabrication method is fully compatible with PDMS microfluidics, which allowed us to integrate a sheath flow based microfluidic cell focusing system with the spectrograph on the same substrate. This integration represents an important step towards a handheld flow cytometer. In addition, as a new class of on-chip optofluidic components, liquid metallic optical elements such as mirrors, gratings and pinholes will likely find other applications for building miniaturized optofluidic systems.

Keywords: Optofluidics, Optofluidic Grating Spectrograph, On-chip spectrometer, Microfluidics, Lab-on-a-Chip, PDMS, Soft Lithography, Liquid Metal, FACS, Biosensor

1. Introduction

Optical spectrometers are an important instrument in physics, chemistry, and biology. In biomedical applications, many optical instruments such as spectrophotometers, microplate readers, and spectral imaging systems employ grating spectrometers as their key components. Such traditional biomedical instruments utilize bulk optics to achieve their functions. Although there were efforts aiming to implement microfabricated grating spectrometer on a number of different substrates such as silicon, glass and III-V semiconductor materials, the fabrication processes proved to be very challenging. In addition, such conventional solid-state materials are not compatible with microfluidics which is often needed for biomedical applications dealing with liquid samples.

The emerging optofluidic technology aims to use liquid-based microfluidic structures to build adaptive and reconfigurable photonic devices, and seamlessly integrate them with microfluidics [1]. A variety of devices such as microfabricated liquid dye lasers [2], reconfigurable photonic crystal circuits [3] and tunable optical fibers [4] have been demonstrated using liquid gain and dielectric materials. However, thus far no metallic optofluidic component has been demonstrated. On the other hand, metal based optical elements such as mirrors, gratings, pinholes and integrating spheres are important for many optical instruments such as grating spectrometers. Here we introduce liquid metallic optofluidic components such as on-chip mirrors and reflection gratings made by filling void polydimethylsiloxane (PDMS) microfluidic structures with liquid gallium alloy. Such metallic components can be used to build wavefront correction adaptive mirrors, ultrawidely tunable diffraction gratings and on-chip spectrometers.

The liquid metal used here is a gallium-indium-tin eutectic alloy (also called Galinstan) that contains 68.5% gallium, 21.5% indium, and 10% tin, and melts at room temperature[5]. Compared with mercury, Galinstan is nontoxic, nonevaporative, and has a higher electrical conductivity and better wetting properties[5][6]. Similar gallium alloys have been used to fabricate on-chip coils, antennas and electrical wires for magnetic, RF and display applications[6-9]. In this work, along with liquid metallic mirrors and gratings, microfluidic components are co-fabricated on the same PDMS substrate, allowing seamless optics/microfluidics integration. Besides optofluidic applications, we believe this technology will also prove an enabling method in the fields of lab-on-a-chip, optoelectronics and flexible electronics by providing novel functions previously difficult, if not impossible, to integrate such as heat management, magnetic coils, tunable antennas, and metallic interconnects components on flexible substrates.

2. On-Chip Liquid Metallic Optofluidic Gratings and Mirrors

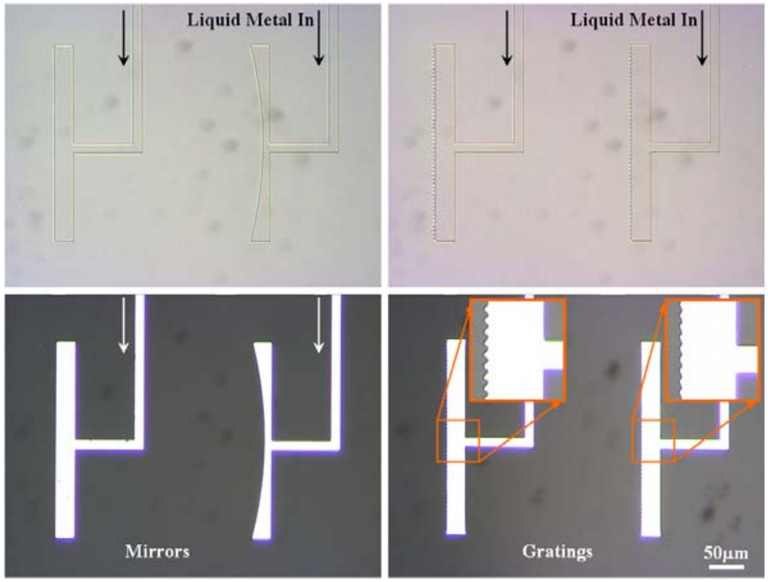

Figure 1 | Optical micrographs of on-chip metallic optofluidic mirrors and reflection gratings. Upper: void PDMS microfluidic structures before filled with liquid gallium alloy. Lower: mirrors and gratings formed after filled with liquid gallium alloy. Insets: enlarged regions of gratings. The grating groove density is 200*g/mm* for both the rectangular and blazed grating. The blaze angle is 30 degree. The radius of curvature of the mirror is 500μm.

Figure 1 shows some fabricated metallic optofluidic components on a monolithic PDMS chip using soft lithography as described in Ref [10]. A patterned microfluidic structure when filled with liquid metal can form mirrors and reflection gratings. Thus far, we have made both rectangular and blazed gratings with groove density from 200*g/mm to* 5000*g/mm*, suitable for both low order and high order Echelle spectrometers. With electron beam lithography, we can further increase the groove density to above 5000*g/mm* which is higher than those of most machine ruled and holographic gratings. As for mirrors, the focal length can be anywhere between a few tens of microns to a few centimeters. An additional advantage of microfabricated mirrors is the ability to fabricate nonspherical shapes which are highly desirable for aberration correction.

3. Design of an On-Chip Czerny-Turner Spectrograph

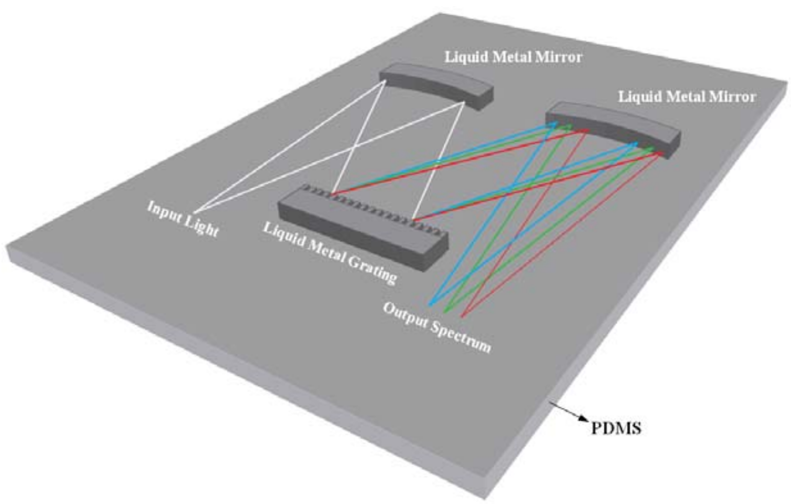

Figure 2. Schematic diagram of a Czerny-Turner optofluidic grating spectrograph. The grating and mirrors are made by filling microfluidic structures with liquid Gallium alloy.

Conventional grating spectrometers usually consists of the following elements: an input slit, a collimating Mirror, a diffraction grating, an imaging mirror and a linear detector array such as a CCD or CMOS detector. Among the many mounting geometries, the Czerny-Turner mounting is arguably the most popular and flexible arrangement for grating spectrographs employing planar reflection gratings [11]. In this mounting, as shown in Figure 2, two spherical mirrors are used as collimating and focusing elements. The input slit and spectrum plane are located on either side of the grating. We have designed a symmetric Czerny-Turner spectrograph amenable to on-chip implementation using liquid metallic optical components. The details of the design will be given in detail below. In terms of performance, the spectrograph has a footprint of 3cm by 3cm, a resolution of 1.7nm (resolving power *R* ~ 384), a free spectral range (FSR) of 200nm. The grating has a groove density of 200g/mm, a width of 2.5mm and is operated in the 3rd order at 600nm. The incident angle is 7.4 degree. The focal length of the two mirrors is 2.5cm. We assume the detector pixel size to be 10 micron. The focal number of the resulting system is ~F/10. The whole spectrograph is immersed in a two-dimensional slab waveguide with effective index of 1.41. We also designed the spectrograph to satisfy the Rosendahl condition and flat-field condition [11]. The 2D waveguide structure and the small size also contribute to reduce the optical aberrations.

3.1 Free Spectral Range (FSR) and Spectral Resolution

The proposed system will utilize a classical planar Czerny-Turner grating spectrograph [11] as the spectral dispersive component for detecting Raman scattering spectrum in the near infrared regime. The optical design for the spectrograph is shown in Figure 3. The diffraction property of the spectrograph is given by the grating equation:

$$m\lambda = nd(sin\theta + sin\theta') \tag{1}$$

where m is the grating order, λ is the wavelength, n is the refractive index of the medium, d is the grating pitch, θ is the incident angle and θ' is the diffracted angle. The measure of how well a spectrograph separates different colors is given by its angular dispersion:

$$\frac{d\theta'}{d\lambda} = \frac{m}{ncos\theta'} \tag{2}$$

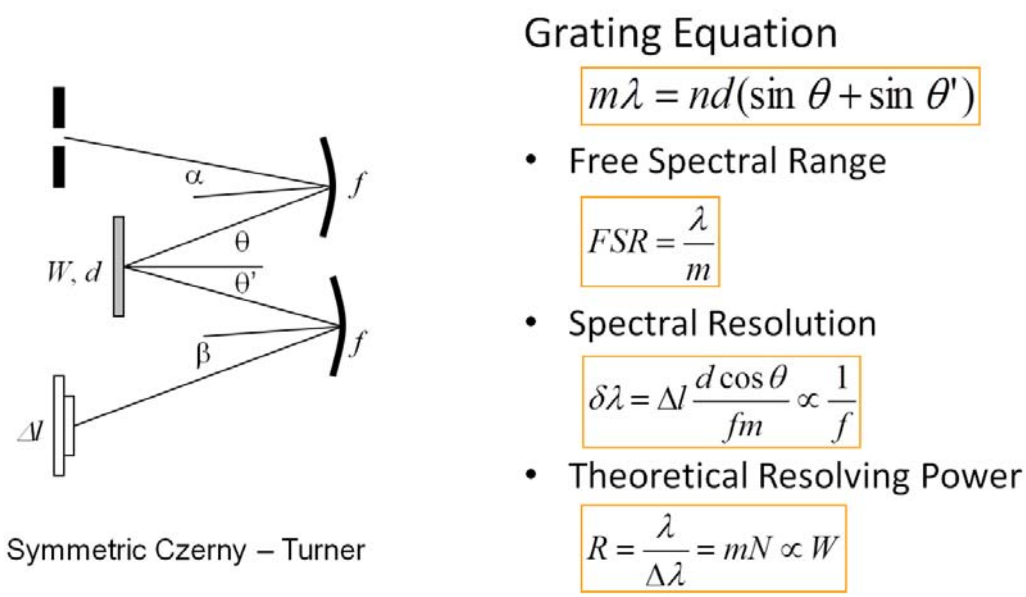

Figure 3. Schematic and geometrical optics picture of the proposed planar optofluidic grating spectrograph. The design equations are shown on the right, and the details are given in the text.

The linear dispersion, that is how far apart different wavelengths separate on the detector, is the product of the focal length f of the exit mirror and the angular dispersion:

$$\frac{dl}{d\lambda} = f\frac{d\theta'}{d\lambda} = \frac{fm}{ncos\theta'} \tag{3}$$

Then the spectral resolution of the spectrograph can be expressed as:

$$\Delta\lambda = \frac{2p}{(dl/d\lambda)} \tag{4}$$

where p is the detector pixel size. The fourth important parameter of a grating spectrograph is its free spectral range (*FSR*), which determines the wavelength range the spectrograph can operate without overlap. It is simply given by:

$$FSR = \frac{\lambda}{\mathrm{m}} \tag{5}$$

If the target performance of the spectrograph is aimed for a typical visible fluorescence spectroscopy requirements, for example: λ = 400nm – 700nm, spectral resolution $\Delta\lambda$ = 1.4nm at 500nm, focal length f = 1cm (determining the device size), input slit width 8µm, and the detector pixel size p = 10µm, then we can determine the grating pitch d and order m from the above equations. Briefly, in our preliminary design, the spectrograph has a footprint of 1cm by 2cm. The grating has a groove density of 500*g*/mm (2µm grating pitch), a width of 5mm and is operated in the 2nd order at 500nm. The incident angle is 7.4 degree. The focal length of the two liquid mirrors is 1cm. We assume the detector pixel size to be 10µm, typical in commercial CCD detector arrays. The whole spectrograph is immersed in a two-dimensional slab waveguide with effective index of n = 1.42, which means light is confined in the vertical direction by optical waveguiding. The thickness of the slab waveguide is 20µm for efficient light collection, and is compatible with typical microfluidic circuits and the fabrication method.

3.2 Aberrations

Three main types of optical aberrations were considered and corrected to make sure that they will not affect the spectral resolution of the spectrograph.

3.2.2 Spherical Aberration

The blur circle due to spherical aberration is given as [11]: $\Delta = \frac{\mathrm{f}}{64\mathrm{F\#}^3}$, where f is the focal length of the imaging mirror and F/# is the focal number of the spectrograph (~6 in this case). The resulting Δ = 0.7um is much less than the 10um detector pixel size.

3.2.2 Coma correction

In our design, the spectrograph satisfies the Rosendahl condition [11], and thus Coma is minimized:

$$\frac{\cos^3\theta}{\cos^3\theta'} = \frac{\cos^3\alpha}{\cos^3\beta}\frac{\sin\beta}{\sin\alpha} \tag{6}$$

Because of the 2D waveguide structure, no astigmatism exist in this system.

3.3 Flat Field Condition

Due to the fact that all available optical detectors are 2D flat detectors, it is important to minimize the field curvature at the output plane. The field curvature is zero when the following condition is satisfied [11]:

$$\begin{gathered}\frac{2}{\mathrm{f}} + \frac{3\mathrm{Z}}{\mathrm{f}^2} + \frac{3}{4}\frac{\mathrm{Z}^2}{\mathrm{f}^3} = 0 \\ \mathrm{Z} = 2(1 - 1/\sqrt{3})\mathrm{f}\end{gathered} \tag{7}$$

where Z is the distance between the grating and the imaging mirror. In our design, we chose the imaging mirror position to satisfy the flat field condition.

4. Fabrication

The fabrication of the on-chip grating spectrograph uses conventional repica moding soft lithography as shown in Figure 4. A PDMS device with void spectrograph-shaped structures was fabricated using replica molding soft lithography [10]. Then Gallium-Indium-Tin alloy liquid metal was filled into the structure to form a planar grating spectrograph.

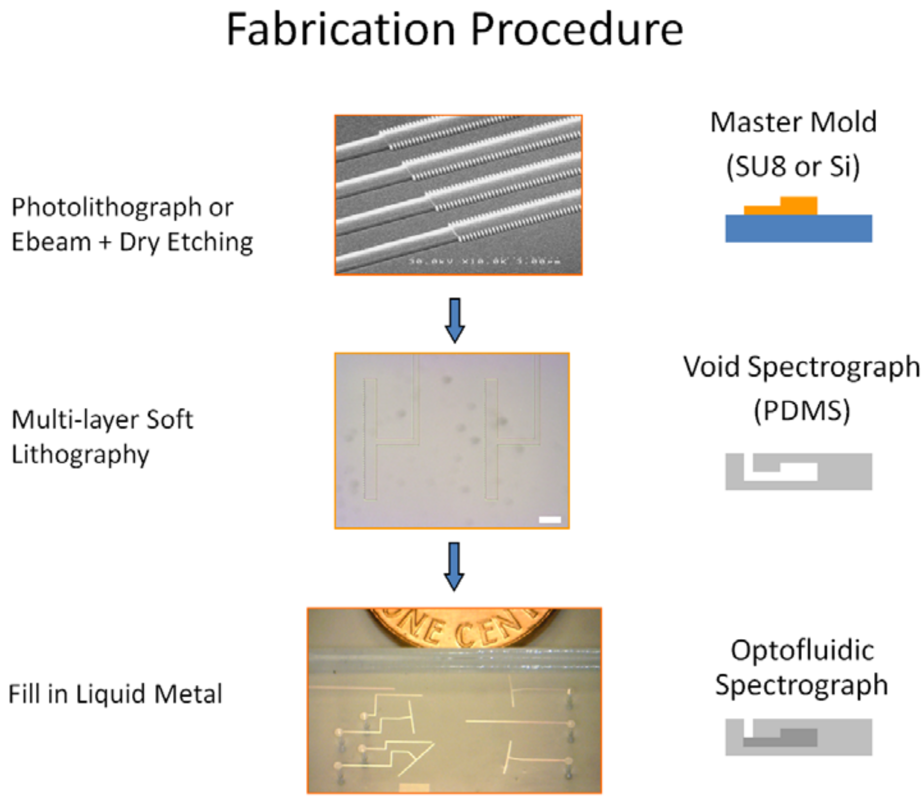

Figure 4. Fabrication procedure for the on-chip optofluidic grating spectrograph.

5. Results

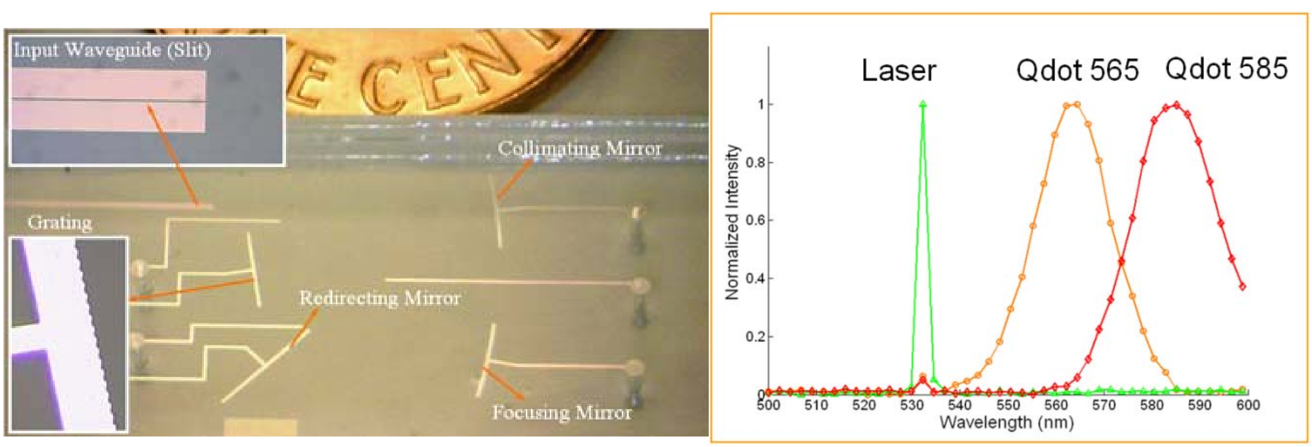

Figure 5. **Left:** optical micrograph of an on-chip planar optofluidic grating spectrograph fabricated in PDMS. The metallic mirrors and grating are made by filling in the void PDMS structure with Ga-In-Tin liquid metal. The whole chip measures 1cm by 3cm . **Right**: typical measured normalized fluorescence spectra from quantum dots Qdot 565 and Qdot 585. The spectral resolution achieved was ~1.4nm.

An on-chip grating spectrograph used for fluorescence detection is shown in Figure 5. The spectrograph was able to distinguish more than 10 different fluorophores in the visible region, whose emission spectra are separated by > 20nm. The whole chip measures 1cm by 3cm . We were able to use it to measure fluorescence emission spectra from quantum dots Qdot 565 and Qdot 585. The spectral resolution achieved was ~1.4nm. The spectrograph is fully compatible with PDMS microfluidics.

7. SUMMARY

We have demonstrated liquid gallium alloy based metallic optofluidic components including mirrors and reflection gratings on a PDMS chip. The fabrication and operation of the components is fully compatible with PDMS based microfluidics technology [12][13]. Using such on-chip liquid metallic optofluidic components, we demonstrated an on-chip Czerny-Turner spectrograph with 1.4nm spectral resolution and a footprint of 1cm by 2cm. This integration represents an important step towards a handheld spectrometer based biomedical instruments. In addition, as a new class of on-chip optofluidic components, liquid metallic optical elements such as mirrors, gratings and pinholes will likely find other applications for building miniaturized optofluidic systems.

REFERENCES

1 D. Psaltis, S.R. Quake SR and C.H. Yang, "Developing optofluidic technology through the fusion of microfluidics and optics", Nature, 442 (27), 371-386 (2006).

2 Z.Y. Li, Z.Y. Zhang, T. Emery, A. Scherer and D. Psaltis, "Single mode optofluidic distributed feedback dye laser", Optics Express, 14(2), 696-701 (2006).

3 D. Erickson, T. Rockwood, T. Emery, A. Scherer and D. Psaltis, "Nanofluidic tuning of photonic crystal circuits", Optics Letters, 31(1), pp 59-61, (2006).

4 P. Mach, et al. "Tunable microfluidic optical fiber". Appl. Phys. Lett. 80, 4294–4296 (2002).

5 Lyon, R.N. (ed.) Liquid-Metals Handbook (Atomic Energy Commission, 1954).

6 Cheng, S., Rydberg, A., Hjort, K., & Wu, Z. Liquid metal stretchable unbalanced loop antenna. Appl. Phys. Lett. 94, 144103 (2009).

7 Dickey, M.D., Chiechi, R.C., Larsen, R.J., Weiss, E.A., Weitz, D.A. & Whitesides, G.M. Eutectic gallium-indium (EGaIn): a liquid metal alloy for the formation of stable structures in microchannels at room temperature. Adv. Funct. Mater. 18, 1097–1104 (2008).

8 Siegel, A.C., Shevkoplyas, S.S., Weibel, D.B., Bruzewicz, D.A., Martinez, A.W., & Whitesides, G.M. Cofabrication of electromagnets and microfluidic systems in poly(dimethylsiloxane). Angew. Chem. Int. Ed. 45, 6877 –6882 (2006).

9 Kim, H.J., Son, C. & Ziaie, B. A multiaxial stretchable interconnect using liquid alloy-filled elastomeric microchannels. Appl. Phys. Lett. 92, 011904 (2008).

10 Y.N. Xia and G.M. Whitesides, "Soft lithography," Annu. Rev. Mater. Sci. 28, 153-184 (1998).

11 J. James, Spectrograph Design Fundamentals, (Cambridge, 2007), Chap. 8.

12 M.A. Unger, H.P. Chou, T. Thorsen, A. Scherer and S.R. Quake, "Monolithic microfabricated valves and pumps by multilayer soft lithography," Science, 288, 113-116 (2000).

13 Thorsen, T., Maerkl, S.J., & Quake, S.R. Microfluidic large scale integration. Science 298, 580-584 (2002).

Acknowledgements

Z.Y.L. acknowledges the faculty start-up fund provided by the School of Engineering and Applied Science at The George Washington University.