High-contrast Brillouin spectrometer based on a hybrid VIPA-etalon cascade scheme

Sophie Chagnon-Lessard[1,2], Ian Miller[1], John Hunter[1], Kevin Gourley[1], Hubert Jean-Ruel[2]*
[1]LightMachinery Inc., 80 Colonnade Road North, Nepean, ON K2E 7L2, Canada
[2]Department of Electronics, Carleton University, Ottawa, ON K1S 5B6, Canada
*hubertjeanruel@cunet.carleton.ca

ABSTRACT

Brillouin spectroscopy is increasingly employed for biomedical research and recent advances such as line-scanning configurations further widen the scope of possible measurements. Current spectrometer technologies have limitations which are prohibitive for certain applications. We propose a novel hybrid VIPA-etalon cascade scheme compatible with both confocal and line-scanning geometries. A single VIPA is followed immediately with one or multiple essentially parallel-oriented standard Fabry-Perot etalons of approximately matching thickness. The cascaded etalons preserve near-unity throughput while increasing the contrast by more than 20 dB per stage. Other advantages include simplicity, compactness, and wavelength flexibility. We present simulations of the hybrid VIPA-etalon scheme and an experimental proof-of-concept measurement.

Keywords: Brillouin spectroscopy, contrast enhancement, line-scanning, VIPA, etalon

1. INTRODUCTION

Brillouin spectroscopy is establishing itself as an invaluable tool for probing non-invasively the mechanical properties of tissues in the context of biomedical research and diagnostics [1]. For many applications, 2D or 3D Brillouin imaging is of particular interest. The recently developed line-scanning geometries open up new possibilities in terms of mapping speed [2,3]. These modalities are incompatible however with the widely used high-contrast two-stage cross-axis VIPA scheme [4]. Alternative contrast-enhancing strategies exist but they have limitations which are prohibitive for certain applications. Apodization is compatible with line-scanning but only a single stage (~20 dB) can be implemented. Narrow-band notch filtering with rubidium cells has been implemented successfully (~40 dB per stage), but it constraints the measurement to the near-infrared region. Given the λ^{-4} dependence of the Brillouin signal magnitude and the typical quantum efficiency curves of cameras, visible excitation is often desired. To address this technological gap, we built on our previous work [5] and developed a novel high-contrast and high-throughput hybrid VIPA-etalon cascade scheme compatible with both confocal and line-scanning schemes. It is presented below, along with simulations and proof-of-concept measurements.

2. METHODS

The simulations were performed using a MATLAB program based on standard Fabry-Perot and imaging equations. The simulation parameters are provided in the main text. The proof-of-concept measurements were performed using a 457 nm single longitudinal mode laser (Cobolt 05-01 Series, Hübner Photonics), a single mode fiber, a thickness-matched VIPA/etalon pair (thickness ~1.36 mm; VIPA finesse ~70; etalon finesse ~35), off-the-shelf optics, and a CMOS camera.

3. RESULTS AND DISCUSSION

The proposed configuration is shown schematically in Fig. 1. The collected scattered signal is coupled to a single VIPA with a cylindrical lens. The VIPA is followed with one, two, or more approximately parallel-oriented standard Fabry-Perot etalons with approximately matching thickness. In contrast to VIPAs, which have near-unity throughput, etalons typically have a throughput on the order of inverse finesse when illuminated with cylindrically diverging light (Fig. 2a, middle panels). In the proposed configuration however, they transmit nearly all the incident light (Fig. 2a, bottom panel) since the upstream VIPA pre-sorts each frequency component precisely at the angles of maximum etalon transmission, given the

Optical Elastography and Tissue Biomechanics XI, edited by Kirill V. Larin, Giuliano Scarcelli,
Proc. of SPIE Vol. 12844, 1284403 · © 2024 SPIE
1605-7422 · doi: 10.1117/12.3008831

matching dispersions. Consequently, the cascaded etalon(s) preserve near-unity throughput while greatly enhancing the contrast since they reflect the small fraction of photons transmitted by the VIPA at angles other than the actual VIPA orders. The cascaded etalon(s) must have the same vertical tilt as the VIPA (the reference frame is given in the caption of Fig. 1) to produce matching dispersion. They must have slightly different horizontal tilt and physical thicknesses to prevent undesired secondary reflections from falling on the target region of the sensor while having matching effective thicknesses.

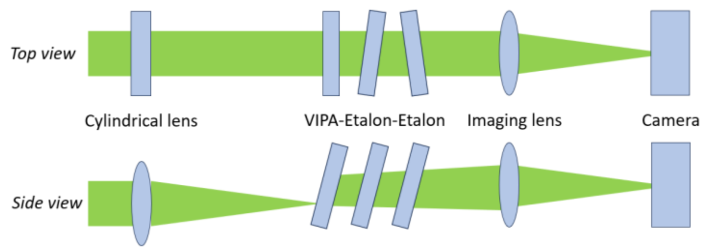

Figure 1. Schematic of the proposed configuration. The case shown here includes two contrast enhancement stages. The labels "top" and "side" views refer to a VIPA orientation for which the dispersion axis is vertical.

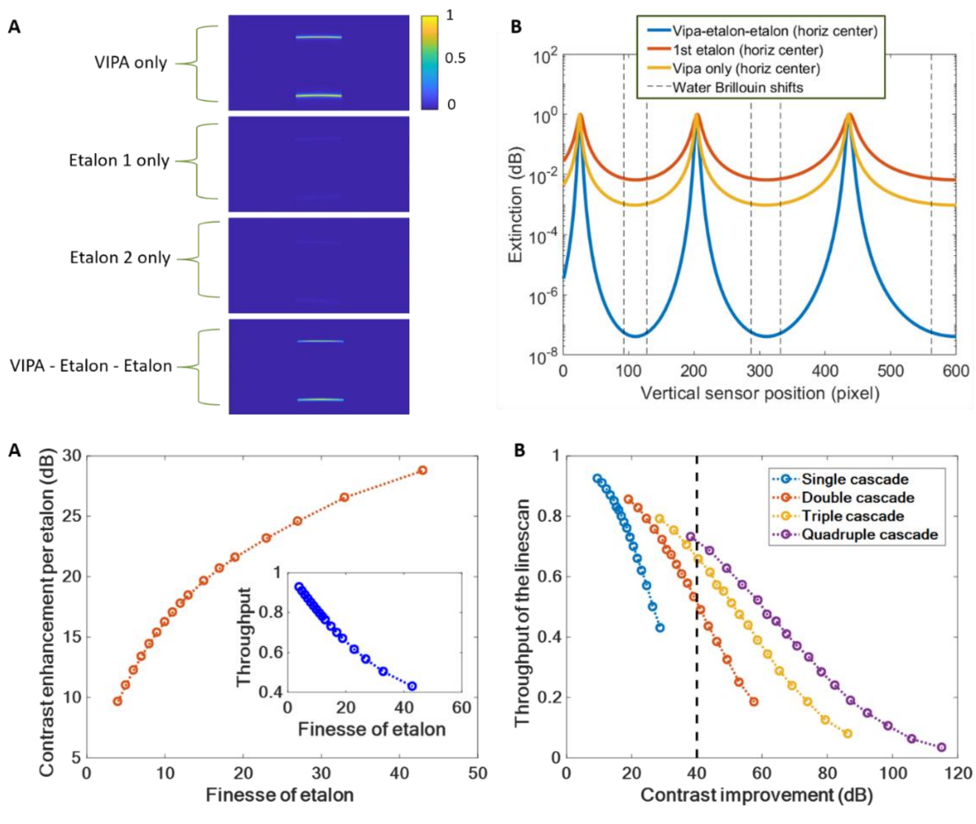

Figure 2. Simulation of a potential VIPA-etalon-etalon design illuminated with the excitation wavelength only (simulation details are provided in the text). A) Simulated sensor images for 4 cases: VIPA only, etalon 1 only, etalon 2 only, and all 3 elements combined. The 4 images are normalized to the VIPA-only case. B) Comparison of the simulated spectral response (uncalibrated and normalized to the VIPA-only case) of the excitation wavelength with and without the cascaded etalons. C) Simulation of the contrast enhancement upon the addition of a single cascaded etalon as a function of its finesse. Inset: VIPA-etalon throughput as a function of the etalon finesse. D) Simulation of the throughput as a function of the cascade-induced contrast enhancement in line-scanning geometry for a single, double, triple, or quadruple cascaded etalons.

A specific VIPA-etalon-etalon design was simulated and its throughput and contrast were assessed. The results are shown in Fig. 2a,b. All 3 components have a free spectral range (FSR) of 15 GHz and a vertical tilt of 1°. The finesse of the VIPA is 55 while that of the etalons is 19. The horizontal tilt of the VIPA is 0° while that of the two etalons is 0.08° and -0.08°. The excitation wavelength is 660 nm. A 150 µm line-scan image is assumed (corresponding to a 3:1 magnified 50um line-scan excitation collected with a 0.4 NA objective). Two FSRs are significantly illuminated and reported. The camera and imaging lens parameters are inconsequential since they only scale the image. The resulting simulated performances are as follow: 0.27 GHz FWHM resolution; ~50% throughput; and 75 dB contrast. Fig. 2c presents the simulated dependence of the throughput and contrast enhancement (per stage) on the etalon finesse. The resulting relationship between contrast improvement and throughput is shown in Fig. 2d for various numbers of cascade stages. The results suggest that implementing several stages consisting of low-finesse etalons is desirable over a single high-finesse stage. Combined with various practical considerations, 2 to 4 cascade stages is likely ideal.

An experimental proof-of-concept is presented in Fig. 3. A single frequency laser was coupled via a single mode fiber to a collimator and steered towards a setup similar to that shown in Fig. 1 (albeit with a single cascade stage). The single mode fiber mimics confocal collection. The experimental parameters, which are provided in the methods section, are different but comparable to those used for the simulations presented in Fig. 2. While the VIPA-only case (Fig. 3a) exhibits significant signal between VIPA orders, where the Brillouin signals would be expected, it is essentially eliminated in the VIPA-etalon case (Fig. 3b). A contrast enhancement of ~ 20 dB is achieved with less than 2 dB of insertion loss. Interestingly, scattered light along the orthogonal direction is also eliminated, thanks to the horizontal tilt of the etalon.

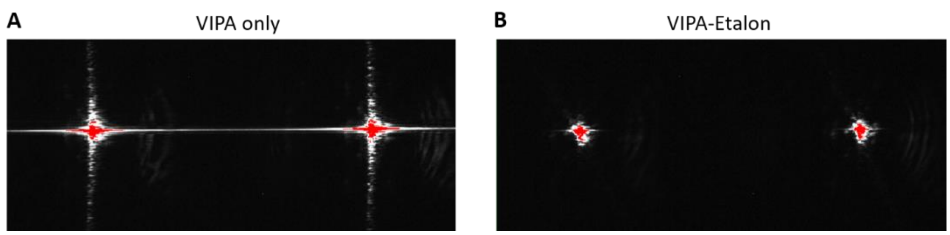

Figure 3. Saturated experimental sensor images showing 2 laser orders (457 nm) using a VIPA (A) and a VIPA-etalon cascade (B). The dispersion axis is horizontal. Saturated pixels are shown in red.

4. CONCLUSIONS

A Brillouin contrast enhancing strategy consisting of cascading thickness-matched etalons downstream of a VIPA was demonstrated. Simulations and preliminary experimental measurements showed an achievable contrast enhancement greater than 20 dB per etalon stage while preserving a high throughput. The proposed configuration can reach >75 dB contrast and is compatible with both line-scanning and standard confocal geometries, at any wavelength. It is also simple, robust, compact, and amenable to monolithic embodiments, making it a promising candidate for the next generation of bio-Brillouin systems.

ACKNOWLEDGEMENTS

We thank the rest the spectrometer and optic teams at LightMachinery for their help and support.

REFERENCES

[1] Robert Prevedel, Alba Diz-Muñoz, Giancarlo Ruocco, and Giuseppe Antonacci, "Brillouin microscopy: an emerging tool for mechanobiology," Nature methods. 16(10), 969-977 (2019). DOI: 10.1038/s41592-019-0543-3

[2] Jitao Zhang, Milos Nikolic, Kandice Tanner, and Giuliano Scarcelli, "Rapid biomechanical imaging at low irradiation level via dual line-scanning Brillouin microscopy," Nature Methods. 20(5), 677-681 (2023). DOI: 10.1038/s41592-023-01816-z
[3] Carlo Bevilacqua, Juan Manuel Gomez, Ulla-Maj Fiuza, Chii Jou Chan, Ling Wang, Sebastian Hambura, Manuel Eguren et al. "High-resolution line-scan Brillouin microscopy for live imaging of mechanical properties during embryo development," Nature Methods. 20(5), 755-760 (2023). DOI: 10.1038/s41592-023-01822-1
[4] Giuliano Scarcelli, and Seok Hyun Yun, "Multistage VIPA etalons for high-extinction parallel Brillouin spectroscopy," Optics express. 19(11), 10913-10922 (2011). DOI: 10.1364/OE.19.010913
[5] Hubert Jean-Ruel, et al. E. S. (2021). US Patent 10,996,109. Washington, DC: U.S. Patent and Trademark Office.