Towards a label free coherent detectorless imaging module in photonic integrated circuits

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ABSTRACT

We discuss and present preliminary experimental evidence of three novel add-on functionalities that can make Optical Feedback Imaging a truly small footprint and label-free bioimaging technology. The first is single-pixel compressed sensing. Here we report on scanless optical feedback imaging in free space by spatially modulated illumination of the target. The second is chemical sensitivity. Here, we report the identification of several pigments by selective spectral discrimination at three different wavelengths. The third functionality is the integration of OFI in silicon photonic chips. Here we identify the building blocks necessary to implement a scanless imaging system in an integrated photonic chip and show evidence of laser modulation through optical feedback provided by the emitted radiation after passing through a silicon passive integrated waveguide.

Keywords: Coherent imaging, Optical feedback interferometry, Laser self-mixing, Photonic Integrated Circuit, Single-pixel coherent imaging

1. INTRODUCTION

Early-stage lesions, both inflammatory and malignant, originate mainly from epithelial tissue. Imaging is an essential screening and diagnostic tool at almost every step of clinical management. In an idealistic medical perspective, an imaging system should span an unreasonably wide range in the space, time, and frequency domains. Should be able to record images at video rates, possibly with subcellular resolution, across the whole volume of interest. At the same time, its spectral extension should allow for visible and infrared imaging, warranting long-term calibration stability to follow the evolution of slow biochemical and biomechanical processes. In the real world of clinical management, there are instead several imaging systems specialized to high acquisition speed or long-term stability, subcellular or wide field resolution, visible or infrared radiation, volume, or surface scan.[1]

Imaging of the mucosal walls of the interior of hollow organs or cavities is much more challenging, and imaging opportunities in clinical practice are pretty much limited to white-light endoscopy, possibly assisted by optical adjunct technologies such as hyperspectral or autofluorescence imaging, optical coherence tomography, or spectroscopic techniques such as Raman, light scattering, or diffuse reflectance.[2]

Without pretending to be a "be-one-be-all" technology, coherent imaging based on optical feedback interferometry (OFI) has recently advanced in many of the relevant ranges noticed above. OFI in semiconductor lasers can be conveniently recorded without any external detector to measure down to nanoscale displacement[3] just by measuring the voltage change at the laser terminals, a feature that allows compact imaging at pretty much any wavelength where a semiconductor laser exists, from UV to FIR.[4] In fact, imaging capabilities have been demonstrated in visible, near-infrared, mid-infrared, and THz spectra,[5] also with diagnostic specificity.[6] High-speed acquisition capable of tracking eye movement has recently been implemented in augmented reality displays,[7] while thermally stabilized quantum cascade lasers have allowed acquisitions over a few days of continuous operation.[8] Being inherently confocal,[9] OFI allows volume scanning down to the penetration depth available at the

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wavelength of use. To further improve OFI portability, in-fiber applications[10] and, quite recently, applications in silicon photonics integrated circuit (PIC)[11] have also been demonstrated.

We discuss and present preliminary experimental evidence for three novel add-on functionalities that can make OFI a truly small footprint and a label-free bioimaging technology.

The first functionality is single-pixel compressed sensing. Here, we report on scanless OFI in free space by spatially modulated illumination of the target. Single-pixel sensing allows for scanless imaging, thus sensibly reducing the speckle noise inherent in any coherent scanning imaging system.

The second functionality is chemical sensitivity. Here we report the identification of several pigments by selective spectral discrimination at three different wavelengths. OFI is inherently phase sensitive, allowing for the detection of very small signal changes encoded in the optical frequency (FM). The demonstration of direct signal amplitude change sensitivity (AM) opens new imaging capabilities due to differential absorption contrast, especially interesting in the mid-infrared molecular fingerprint spectral range.

The third functionality is the integration of OFI in silicon photonic circuits. Here, we identify the building blocks necessary to implement a scanless imaging system in an integrated photonic chip and show evidence of laser modulation through optical feedback provided by the emitted radiation after passing through a silicon passive integrated waveguide.

The small footprint of photonic integrated circuits, together with the all-in-one source and detector compactness, would make OFI eligible as the adjunct optical technology of choice for many white-light endoscopic probes, implementing multi-modality capability, like morphological, chemical, and depth-resolved imaging.

2. SCANLESS SINGLE PIXEL IMAGING

Advanced scanless (or single-pixel) imaging techniques and algorithms based on compressed sensing (CS), can be used to reconstruct the image of a composite target. Although the principle of single-pixel imaging through CS has been used in free space in several application contexts, the first proof-of-principle demonstration in OFI configuration has been very recently obtained by one of the authors.[12] The illumination of the sample is accomplished by projecting random intensity profiles generated by a Spatial Light Modulator onto the sample surface. The light backscattered by the sample and collected by the laser, depending on the illumination pattern, exploits the laser self-mixing effect changing both the laser power and the laser terminal voltage. The CS algorithm evaluates the complex amplitude of the laser mode for different intensity profiles and extrapolates an image of the object.

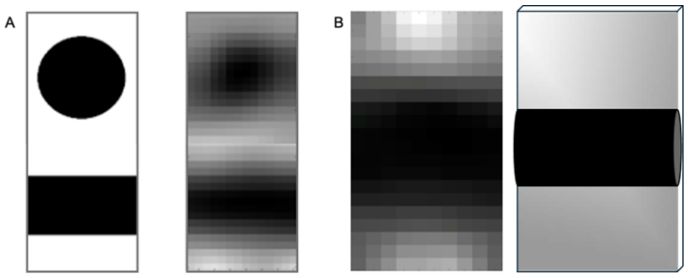

Figure 1. (A) Peak-Signal-to-Noise ratio simulated image of a simple target symmetry (100% absorptive circle and rod on a perfectly 100% reflective background) after 2000 measurements (patterns). Originally published in.[12] (B) Experimental measurement based on 37 patterns of a straight wire on a mirror, sketched at the rightmost panel. Adapted from a figure originally published in.[13]

The originality and appeal of the CS was recently caught by another group who integrated a single pixel imaging device in an NIR PIC using a chip-scale integrated optical phase array combined with a 3D waveguide, to realize the needed spatial light modulator.[14]

At contrast with neural network-based algorithms, CS does not require intensive preliminary training, since it works by searching the non-common features in any set of illumination pattern integrals (measured backscattered intensity). Figure 1 shows the proof-of-principle of the discrimination ability of CS-OFI comparing simulated and experimental results for a simple full-contrast target image.

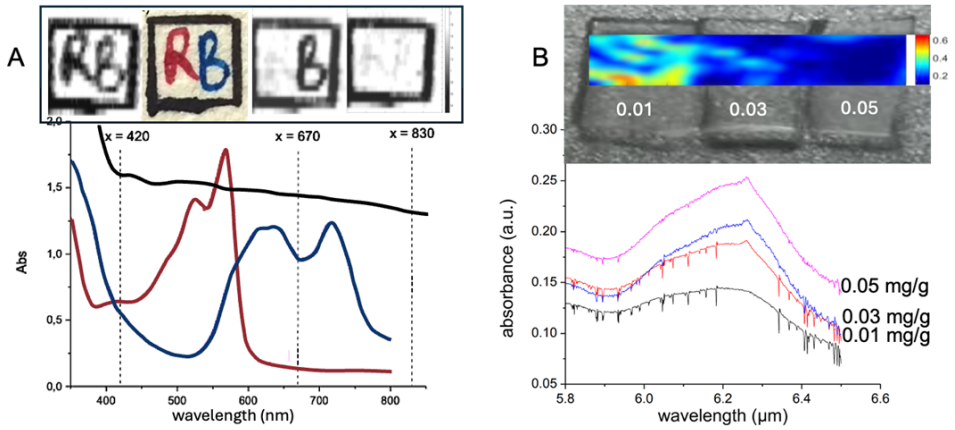

Figure 2. (A) Measured absorption spectra of the three pigments used to draw "RB" in the black frame shown on top. The black-white pictures are OFI scans collected at the three wavelengths of 420 nm, 670 nm and 830 nm. Adapted from a figure originally published in.[18] (B) Measured absorption spectra of the three PDMS samples shown in the photo in the top. Each sample contains a different concentration of potato starch (0.01 mg/g, 0.03 mg/g and 0.05 mg/g in weight). The blue inset is the OFI scan of the central portion of the three samples collected by a MIR-QCL laser at 6.27 μm. Adapted from a figure originally published in.[19]

3. LABEL FREE CHEMICAL IMAGING

Biological imaging is no longer restricted to visible light or surface morphological information: in particular, NIR wavelengths can propagate a few centimeters inside hydrated tissues as a result of the water transparency window. Although invisible to the eye, semiconductor technology (Si, Ge, InGaAs) has made sensitive NIR imaging devices available. The spectral range between NIR and microwaves, used in NMR images, is lagging behind due to the scarcity of efficient sources, although the MIR and FIR regions host a wealth of important optically addressable information, potentially very useful for diagnostics at the biomolecular level.[15] The high absorbance of water has so far led to the investigation in these spectral regions of dehydrated (ex vivo and in vitro) samples in the transmission configuration.[16] The recent advancement of OFI-QCL technology is changing the perspective scenario by exploiting pulsed laser operation, opening new opportunities for chemical microscopy in tissues and materials in reflection mode, beyond micro-Raman spectroscopy.[17]

OFI, like any other coherent imaging, is primarily sensitive to the refractive index contrast in the sample, that determines the phase shift detected in the signal. Unlike conventional interferometry, where the contrast of amplitudes in the sample is poorly translated into an intensity change detected in the signal, OFI acts more like a heterodyne detector, where the small-amplitude signal is amplified by the strong local oscillator field.[20]

Thus, direct absorption images in reflection mode are relatively easy to take even from a non-cooperative diffusive target, as shown in Figure 2A. Three different lasers were used to take images of a paper sheet colored with three different pigments, the absorption spectra of which are shown in the lower part of the panel. The laser wavelengths were chosen to allow for a differential identification of the pigments. The OFI images are shown at the top of the figure together with a conventional photo of the target. The color of the pigments can be assigned through the lookup Table 1.

Table 1. Lookup table that can be used to identify the unknown pigment by measuring the signal at the selected wavelengths.

	Blue laser	Red laser	NIR laser
Blue ink	Yes	Yes	—
Magenta ink	Yes	—	—
Black ink	Yes	Yes	Yes

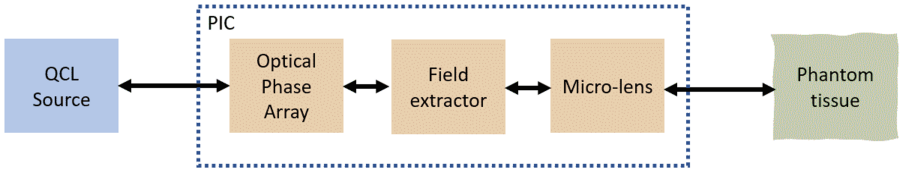

Figure 3. Diagram of the building blocks of a Silicon Photonics chip for integrated OFI.

4. SILICON PHOTONIC CIRCUITS

The third technology that we address is based on OFI in integrated optical circuits. The first experimental report of laser self-mixing propagated through a PIC, refers to the implementation of a FM to AM filter in silicon nitride waveguides.[11]

Here we propose to extend the PIC functionality to include the control of the feedback coefficient and the illumination of the target by an Optical Phase Array (OPA)[21] used as a spatial light modulator[14] for the structuring of the light field required by single-pixel imaging. The functional blocks of the PIC are depicted in (Figure 3).

As a first experimental demonstration towards this direction, we consider the setup shown in Figure 4A. There, a conventional diode laser that emits at 1.5 µm is fiber-coupled to a photonic chip grown at IMEC containing an integrated optical waveguide. The 2 mm long silicon waveguide has a width of 450 nm and a height of 220 nm embedded in silicon oxyde, as a standard for silicon photonic components operating at the selected wavelength. The mirror is placed on a piezoelectric stage. Light is coupled to and from the PIC by optical fibers and directed on the mirror surface by a variable collimator. The back-reflected radiation recombines in the laser source following the same path. The interferometric signal is monitored using the photodetector directly integrated in the laser package; The resulting electrical signal is amplified and visualized on an oscilloscope (Figure 4B), showing the sawtooth interference fringes corresponding to the periodic motion of the mirror.[22]

Figure 4B shows the signal acquired from a stationary mirror by applying a triangular modulation to the current drive of the lasers. The photocurrent (in red) shows small 'fringes' superposed to the laser output power

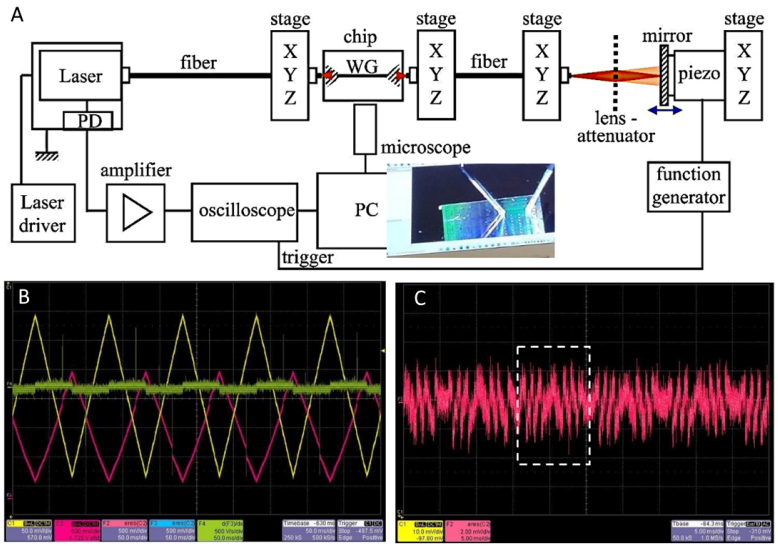

Figure 4. (A) Experimental setup; the picture in the inset is a photo of the fiber coupling to the PIC. (B) Optical feedback signal (red trace) collected from a fixed mirror by applying a triangular modulation to the laser current (yellow trace), and its derivative (in green). (C) Optical feedback fringes collected by applying a sinusoidal displacement to the mirror; the dashed box identifies a single period.

slopes, which can be enhanced by AC coupling and further derivation. Figure 4C shows the signal acquired by applying a sinusoidal waveform to the piezo actuator that controls the mirror displacement.

This device can be, therefore, used both to reconstruct the displacement and the direction of motion of the target (in this setup, the mirror), using the laser as a source and detector at the same time, and to measure dielectric features of a stationary target, as in the previous section.

5. CONCLUSIONS

In conclusion, we presented the experimental evidences supporting the development of OFI PICs compatible with the footprint of endoscopic devices and with spectral extension from the visible to the mid infrared.

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