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# Dual-comb interferometry using frequency shifting loops

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**Abstract.** Dual-comb systems have demonstrated their potential for metrology, e.g. spectroscopy vibrometry or ranging [1]. However, the implementation of dual-combs is often complex and generally requires substantial optical and optoelectronic hardware. Here, we propose a simple and compact architecture based on a bidirectional frequency shifting loop, that provides more than 100 mutually coherent comb lines. The system makes use of a CW laser and a slow electronic detection chain (10 MSa/s). We have implemented two configurations enabling dynamic multi-heterodyne interferometry at 20kHz: the first one makes use of acousto-optic frequency shifters, and allows highly sensitive distributed acoustic sensing along a fiber. The second one involves electro-optic frequency shifters, and enables ranging with a sub-mm resolution.

## Introduction

Optical sensing systems are of considerable interest for numerous applications. Conventional ranging is based on time-of-flight measurement and therefore has limited resolution and range. Coherent techniques are more efficient because their range scales as 1/r and are sensitive to the optical phase, enabling velocimetry based on Doppler effect. Multi-heterodyne or dual-comb techniques are particularly appealing, beacause they combine a high spatial resolution with a slow detection chain. However, the practical generation of dual-combs is generally complex, involving costly broadband lasers and/or high power signals in the GHz range. Here, we propose a simple architecture combining scalability and high performance, based on frequency shifting loops (FSL). We report two experimental implementations of the same concept, enabling respectively high sensitivity distributed acoustic sensing, and lidar with a sub-mm resolution.

## 1 Bidirectional frequency shifting loop

The architecture is based on bidirectional FSL (Bi-FSL) i.e. a fibered loop seeded in both directions by a CW laser. The loop contains an amplifier that compensates for the loss in the loop, a bandpass filter to set the bandwidth of the output signals and to limit the ASE generated by the amplifier, and two frequency shifters placed between two circulators. Depending on the direction of rotation in the loop, the light is submitted to different frequency shifts, $f_{s1}$ and $f_{s2}$. Then, the FSL output consists of two mutually coherent frequency combs of spacing $f_{s1}$ and $f_{s2}$. We define N as the number of lines per comb.

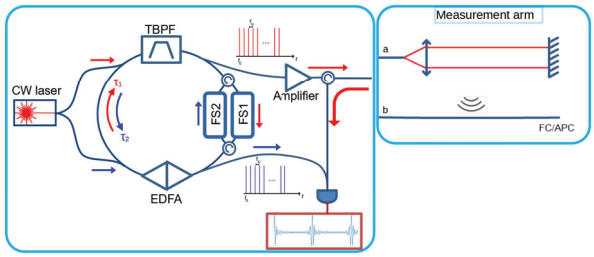


**Fig. 1.** Bidirectional frequency shifting loop, the measurement arm can be (a) a telemetric system with a collimator and a target or (b) a distributed acoustic sensor

As in the conventional dual-comb systems, one comb is used as a probe while the other is a reference. The Hilbert transform of the signal obtained by recombining the two combs on a detector after low-pass filtering gives access to the reflectivity in amplitude and phase along the probe arm.

Two quantities characterize the dual-comb: the resolution (z) and the ambiguity range (AR):

$$z=\frac{c}{2nf_s} \quad \text{and} \quad AR=\frac{c}{2nNf_s}$$

where c is the speed of light in vacuum and n is the refraction index.

## 2 Bi-FSL with AOMs

The first architecture presented here is a Bi-FSL based on acousto-optics frequency shifters (AOFSs). In our system, the AOFSs impose frequency shifts of 80.000 MHz and 80.020 MHz respectively, which sets the AR to about 2 m.

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This Bi-FSL can be used for coherent lidar in free space (Fig. 1a) [2], or for distributed acoustic sensing (DAS) based on Rayleigh scattering (Fig. 1b) [3].

In this latter case, the probe beam is sent through a 1.5 meter long PM fiber. The detection signal is filtered (4 MHz), and digitally processed (Hilbert transform) to extract the integrated phase along the fiber (Fig. 2a). The computation of the derivative of the cumulated phase provides the absolute variation of the local refractive index along the fiber (Fig. 2b), with a sensitivity of a few $10^{-5}$.

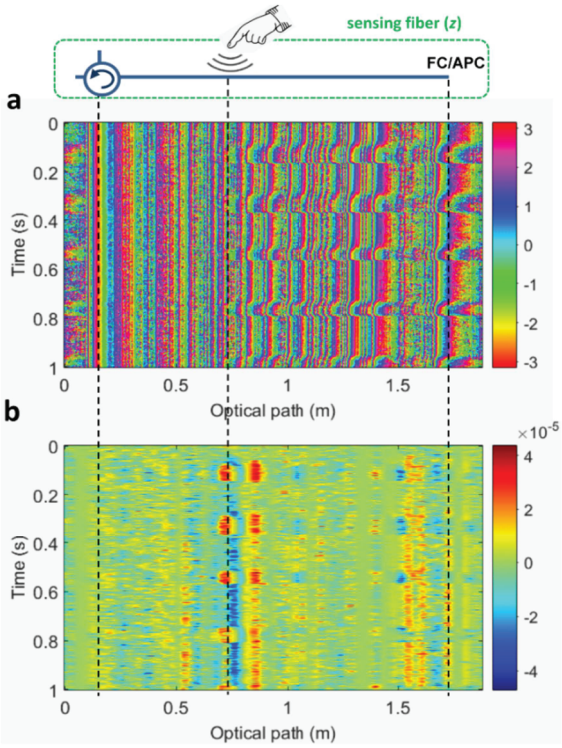


**Fig. 2.** a: Phase profile (in radians) along the sensing fiber when a repeated tapping is applied on it. b: Reconstruction of the refractive index changes (see text)

The temporal resolution is set by the period of the trace, i.e. $1/\Delta f_s$ = 50 µs, while the spatial resolution is equal to 7 mm (corresponding to 200 comb lines).

## 3 Bi-FSL with EOMs

In a second configuration, in order to improve the spatial resolution below the mm of our dual-comb technique, we have implemented a Bi-FSL with larger frequency shifts by replacing the AOFSs by electro-optic frequency shifters based on single sideband modulators. The latter allow frequency shift up to 25 GHz. Initially, we set $f_{s1}$ to 2 GHz and $f_{s2}$ to $f_{s1}$ + 20 kHz. The number of comb lines is now 80, which allows a sub-millimetric resolution.

This Bi-FSL is used, in a free-space lidar configuration, to measure the relative position of a reflective target placed on a translation stage (Fig. 1a). The experimental results are shown in Fig. 3.

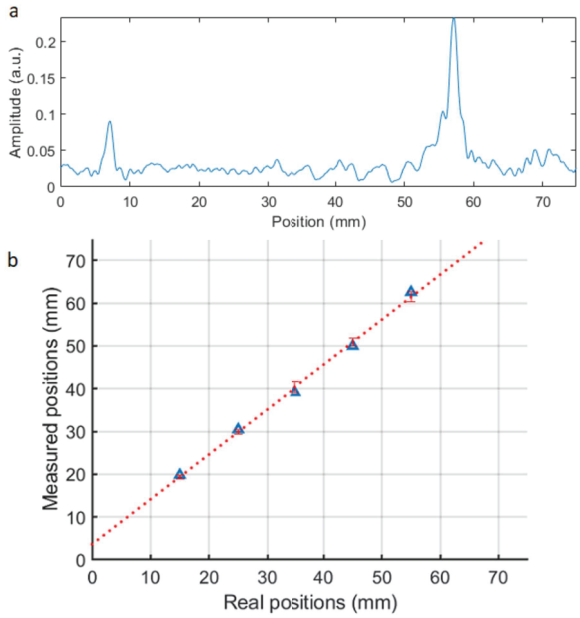


**Fig. 3.** a: Amplitude profile of the signal after reflection on the target. b: Comparison of the real and measured distance, the regression slope is 1,05

The reflectivity profile is mapped in the temporal trace of the output signal. The latter comprises two peaks, the first one is due to a 4 % reflection at the fiber exit and is used as a reference, and the second one is due to the target itself (Fig. 3a). The delay between the two peaks in the output trace is proportional to the relative position of the target, Fig. 3b compares the variation of the distance deduced from the dual-comb trace (y axis) with the distance read on the translation stage (x axis).

## 4 Conclusion

We have shown the interest of the Bi-FSL for dual-comb metrology. In addition to their simplicity, these approaches show a high degree of performance in term of both temporal and spatial resolution, and sensitivity, leading to promising perspectives for DAS and lidar. Additionally, prospects for integration of these systems are now foreseeable in hybrid photonic integrated circuits.

## References

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