We experimentally demonstrate that the spectral sensitivity of a Mach–Zehnder (MZ) interferometer can be enhanced through structural slow light. We observe a 20-fold resolution enhancement by placing a dispersion-engineered, slow-light, photonic-crystal waveguide in one arm of a fiber-based MZ interferometer. The spectral sensitivity of the interferometer increases roughly linearly with the group index, and we have quantified the resolution in terms of the spectral density of interference fringes. These results show promise for the use of slow-light methods for developing novel tools for optical metrology and, specifically, for compact high-resolution spectrometers.

OCIS codes: (120.0120) Instrumentation, measurement, and metrology; (120.3180) Interferometry; (050.5298) Photonic crystals.

http://dx.doi.org/10.1364/OL.41.001431

Slow light has fascinated the physics community for over two decades [1,2]. The slowdown of light has been observed in a diverse range of media, including atomic vapors, optical fibers, and photonic crystals (PhCs) [3]. The ability to manipulate the speed of light has led to a wide variety of technological applications, for example, optical buffers, optical memories, optical modulators, laser radars, and enhanced spectrometers [1,2,4–9].

While not achieving the same extreme slowdown values as material slow light, slow light in nanophotonic devices, particularly in photonic-crystal (PhC) waveguides, has many key advantages. Nanophotonic slow-light structures are extremely compact, with low footprint and high mechanical stability, compared to material slow-light systems [3]. Furthermore, the availability of high-precision fabrication techniques and the use of common materials, e.g., silicon, makes nanophotonic slow light particularly interesting for applications [3–5,7]. Here we demonstrate that structural slow light can dramatically improve the spectral sensitivity of an interferometer. Thus, we combine the enhancement to the spectral sensitivity with the advantages of nanophotonics. Specifically, we place a silicon PhC slow-light waveguide within a compact fiber-based MZ interferometer; see Fig. 1. Our results show an enhancement of a factor of 20 in the spectral sensitivity of the interferometer, without increasing its physical size. This sensitivity is on par with that of previous implementations of material slow-light interferometers [14], using a much more compact slow-light structure (the total PhC footprint is on the order of 0.015 mm²) [14–16]. To demonstrate the advantage of adding a slow-light medium into a spectral interferometer, we discuss the phase difference $\Delta \phi$ between two light beams passing through the two arms of a MZ interferometer. We assume that the phase difference is solely caused by propagation through a length $L$ of slow-light material. The phase difference is defined as

$$\Delta \phi = \frac{\omega}{c} n(\omega)L,$$

where $\omega$ is the frequency of the propagating light, $c$ is the speed of light in vacuum, and $n(\omega)$ is the refractive index of the medium. In practice, $\Delta \phi$ is determined by performing intensity measurements of the interference pattern produced at one of the output ports of the interferometer:

$$I = \frac{I_0}{2} (1 + \cos \Delta \phi),$$

where $I_0$ is the input intensity. The spectral resolution of the interferometer is determined by the minimum resolvable change
I

The local fringe density as

together with the relation between wavenumber and frequency,

where it is assumed that

where the index of the dispersive material as

be significantly higher than the refractive index,

which, in turn, leads to the enhancement of the spectral sensi-
tivity due to structural slow light; see Fig. 1(b).

in optical path length achieved through the imbalance between the two
arms produced by the slow-light region is indicated by

In our experiment, we measure the interference pattern formed at the output
of the MZ interferometer as a function of wavelength \(\lambda\). This
measurement allows us to quantify the enhancement in resolution and sensitivity
through an experimental parameter, the density of fringes per unit wavelength interval, \(N_\lambda\). An approximate expression for the local density of fringes over a small frequency
range \(\Delta\omega\) can be derived by describing the refractive index of the dispersive material as

where \(n_0\) is the refractive index of the material and \(K\) is a constant. The modulation
of the fringe height is due to a resonant effect caused by reflections from the grating couplers of the PhC sample and is not intrinsic to a slow-light interferometer. The increase in fringe density with wavelength is a consequence of the slow-light effect in the PhC waveguide. The experimental measurement, Fig. 2(e), shows the increase in group index as a function of wavelength. As predicted by Eqs. 4 and 5, when the dispersive properties of the material become significant, they lead to an enhancement of the resolution and sensitivity of the device.

We plot the fringe density of the slow-light MZ interferometer as a function of wavelength. The increased density at longer wavelength leads to an increase in the spectral resolution of the device. The red curve in Fig. 3(a) shows the fringe density predicted by our numerical simulation using a plane wave expansion approach (MPB [23]). Further, the expected fringe density of a traditional \((n_0 \approx n)\) MZ interferometer is plotted in green. Clearly, there is a dramatic improvement in the fringe density and, therefore, in the sensitivity of the interferometer, when a slow-light structure is incorporated within it.

For this particular PhC waveguide, our proof-of-principle experiment shows an increase of 20 times in the sensitivity. This number is taken from Fig. 3(a) by calculating the ratio
between the fringe density for the interferometer with (curve in red) and without (curve in green) the dispersive medium at a wavelength of 1556 nm. Further evidence of the role of the group index in determining the sensitivity of the interferometer is shown in Fig. 3(b). In this case, the increased resolution of the device, quantified by its fringe density, exhibits a direct relationship with the group index, as described by Eqs. 3–5. This group index dependence allows one to keep the physical size of interferometers small, creating the potential for compact spectrometers. The spectral sensitivity could be optimized for different applications by engineering the PhC waveguide properties. For instance, further increasing the resolution or creating spectral ranges with a constant enhancement.

In summary, we have demonstrated an enhancement of the spectral resolution, accompanied by enhanced sensitivity, of a MZ interferometer by incorporating a structural slow-light component, in our case, a PhC waveguide. This enhancement, which reached a factor of 20 in our experiment, can be further improved through careful waveguide design. We demonstrated the increased sensitivity through a significant increase in the density of interference fringes. Enhanced-sensitivity interferometers have been an important subject of interest in the photonics community for the last 10 years [1,2,4,5,7,9,10,14–17]. Therefore, we believe that our experimental results are an important starting point for further studies, including on-chip implementations of our device. A monolithic device of this sort would reduce losses and imperfections in our proof-of-principle design. These results provide a path toward a new generation of compact sensitive devices and sensors utilizing light.

**Funding.** National Aeronautics and Space Administration (NASA) (NNX15CM47P); Defense Threat Reduction Agency (DTRA), Joint Science and Technology Office for Chemical and Biological Defense (HDTRA1-10-1-0025); Canada Excellence Research Chairs Program.

**Acknowledgment.** The authors would like to thank David D. Smith and Jerry Kuper for many fruitful discussions.

**REFERENCES**