

Optical Vernier Effect: Recent Advances and Developments

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The optical analog of the Vernier effect applied to fiber interferometers is a recent tool to enhance the sensitivity and resolution of optical fiber sensors. This effect relies on the overlap between the signals of two interferometers with slightly detuned interference frequencies. The Vernier envelope modulation generated at the output spectrum presents magnified sensing capabilities (i.e., magnified wavelength shift) compared to that of the individual sensing interferometers that constitute the system, leading to a new generation of highly sensitive fiber sensing devices. This review analyses the recent advances and developments of the optical Vernier effect from a fiber sensing point-of-view. Initially, the fundamentals of the effect are introduced, followed by an extensive review on the state-of-the-art, presenting all the different configurations and types of fiber sensing interferometers used to introduce the optical Vernier effect. This paper also includes an overview of the complex case of enhanced Vernier effect and the introduction of harmonics to the effect.

1. Introduction

The use of a secondary scale in measuring equipment and instruments, such as in calipers and ancient astronomical quadrants, allows for increasing the resolution and reducing the uncertainty of measurements. The caliper was invented in 1631 by Pierre Vernier.^[1] Some people name such instruments after the inventor, that is, the “Vernier caliper,” wherein the two scales overlapping each other are referred to as the Vernier scale. Eventually, Pierre Vernier may have been inspired by a Portuguese measuring tool from the 16th century called – the Nonius. The Nonius, created in 1542 by the mathematician and cosmographer Pedro Nunes, was a tool used to perform finer measurements on circular instruments, improving the angular measurements of devices like the astrolabe.^[2]

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In the field of optical fibers, the Vernier effect (or the Vernier principle) also left its mark. In 1988, Paul Urquhart was studying and designing compound resonators in optical fibers for application in fiber lasers and optical communications systems.^[3] In this work, Urquhart used the Vernier principle by combining optical fiber rings with unequal lengths in parallel. In this configuration, the Vernier effect acted as a mechanism to suppress spectral modes (suppression of resonance peaks in the spectrum) and to narrow the linewidth of fiber lasers. Moreover, adaptations of the Vernier effect in the fields of optics also led to the development of the optical frequency comb technique, which resulted in the awarding of the Nobel Prize in Physics to

John Hall and Theodor Hänsch in 2005.^[4,5] Such a technique is widely used in Vernier spectroscopy.^[6]

The fast development of many research areas relying on optical fibers, together with the specific technical hurdles in their use, creates new challenges in the fields of optical fiber sensing research. The demand for sensing structures able to achieve higher sensitivities and resolutions than what conventional fiber sensors can offer is growing.^[7] With this, researchers are motivated to find new options for improved optical fiber sensors, enabling access to higher sensitivities and resolutions. The optical version of the Vernier effect applied to optical fiber sensing (Figure 1) has demonstrated a huge potential to solve these needs. In fact, it quickly became a hot topic in this field over the last three years and gained a lot of interest among researchers. The first report that mentions the use of the optical Vernier effect in optical fiber sensors was published by the end of 2012 by Xu et al.^[8] However, it took about 2 years until some of the optical Vernier effect properties, as known today, were reported for optical fiber sensing.^[9] Nowadays, the optical Vernier effect has been used in optical fibers for a large number of different parameters such as temperature, refractive index, pressure, strain, humidity, bending, and others.

This paper reviews the recent advances and developments of the optical Vernier effect applied to optical fiber interferometers. The different configurations used to introduce the optical Vernier effect are analyzed and categorized depending on the type of interferometer and type of configuration employed: single-type or hybrid-type fiber configurations. An overview on extended concepts of optical Vernier effect, namely the complex Vernier effect, which can be reduced or enhanced, and the introduction of harmonics are also explored here, together with different reported applications for each case. Extensive comparison tables are presented in the last section listing published configurations with



Figure 1. Concept figure of the optical Vernier effect for fiber interferometers.

achieved sensitivities and measurement ranges. The paper concludes with a short summary and outlook.

2. Optical Vernier Effect for Fiber Interferometers

The optical version of the Vernier effect relies on the combination of two interferometers, where their interferometric signals can be seen as the Vernier scales. This is illustrated in **Figure 2a**. These two interferometric signals must have slightly shifted interferometric frequencies, or in other words, they must be slightly detuned. With this, the overlap of the two signals generates an envelope modulation, as seen in **Figure 2b**, with enhanced sensing properties in comparison to the native state of the interferometers used. More specifically for fiber sensing, the envelope modulation, also called the Vernier envelope, shows magnified sensitivity over the individual interferometers that constitute the structure, as it will be later discussed. In terms of optical interferometers, the optical Vernier effect can be applied to different kinds of interferometric structures, such as Fabry–Perot interferometers (FPIs), Mach–Zehnder interferometers (MZIs), and Sagnac interferometers (SIs).

When applying the optical Vernier effect, one should have control over the detuning between the signal frequencies of both interferometers. In optical fiber interferometers, the interferometric frequency can be adjusted by modifying their optical path length (OPL). This is achieved by changing the refractive index and/or the physical length of the interferometer. Therefore, given the properties of an initial interferometer (first Vernier scale), the second interferometer (second Vernier scale) can be adjusted to maximize the enhancement provided by the effect.

To perform a measurement with a caliper, one of the Vernier scales slides in relation to the other static scale. Optically, this situation corresponds to applying one of the interferometers as a sensor, whose outcome is typically a wavelength shift as a function of the measurand, while the other interferometer is kept as a reference. Although this is the common way to employ the optical Vernier effect, there are cases where neither of the two interferometers is a stable reference. In such cases, the effect becomes slightly more complex to analyze but, if used properly, it might bring additional enhancements, as will be later discussed in Section 4.

There are two main configurations used to overlap the signal from two optical fiber interferometers in order to introduce the optical Vernier effect: either one can place them in series, or in a parallel configuration. The appearance of the output spectrum might be slightly different for both configurations and it might also depend on the type of optical fiber interferometers that are being used. Nevertheless, the presence of the Vernier envelope modulation and the properties of the effect are still preserved.

2.1. Properties

Taking the example shown in **Figure 2b**, where two Fabry–Perot interferometers are combined in parallel, the measured intensity is described as:^[7]

$$I_{\text{out}} = I_0 - 2AB \left[\cos \left(\frac{2\pi OPL_1}{\lambda} \right) + \cos \left(\frac{2\pi OPL_2}{\lambda} \right) \right] + B^2 \cos \left(\frac{2\pi \delta}{\lambda} \right) \quad (1)$$

where I_0 is an offset, A and B are coefficients related with the reflections at each interface of the Fabry–Perot interferometers, λ is the wavelength, and OPL_1 and OPL_2 are the optical path lengths of the two Fabry–Perot interferometers.

The detuning (δ) between the optical path lengths of the two interferometers used to introduce the optical Vernier effect can be described mathematically by:^[7]

$$OPL_2 = OPL_1 - \delta \quad (2)$$

The reference interferometer, whose optical path length is here denoted by OPL_2 , is typically the one being detuned in relation to the optical path length of the sensing interferometer, here denoted by OPL_1 .

The Vernier envelope modulation is then described by the last term of Equation (1): a sinusoidal behavior with a frequency dependent on the detuning between the two interferometers.

2.1.1. Envelope Free Spectral Range

The free spectral range (FSR) of the Vernier envelope, as marked in **Figure 2b**, can be determined from the phase of the modulation. The phase of the Vernier envelope ($\varphi_{\text{envelope}}$) is given by argument of the last cosine function in Equation (1):^[10,11]

$$\varphi_{\text{envelope}} = \frac{2\pi (OPL_1 - OPL_2)}{\lambda} \quad (3)$$

where λ is the wavelength and OPL_i is the optical path length of the interferometer i , with $i = 1, 2$. The FSR of the Vernier envelope can be expressed as a function of the detuning or also as function of the FSRs of the two interferometers that form the system as:

$$FSR_{\text{envelope}} = \left| \frac{\lambda_2 \lambda_1}{\delta} \right| = \left| \frac{FSR_2 FSR_1}{FSR_2 - FSR_1} \right| \quad (4)$$

where λ_1 and λ_2 are the wavelengths of two consecutive maxima (or minima) of the Vernier envelope, FSR_1 and FSR_2 are the FSRs of the two interferometers, respectively. Since the FSR is a positive quantity, the modulus was applied to all cases in Equation (4). Note that the FSR_{envelope} might become very large (possibly larger than the available spectral range) for small detuning values of δ .

2.1.2. Magnification Factor (M-Factor)

The magnification factor (M -factor) is an important quantity used to characterize the optical Vernier effect. This quantity estab-

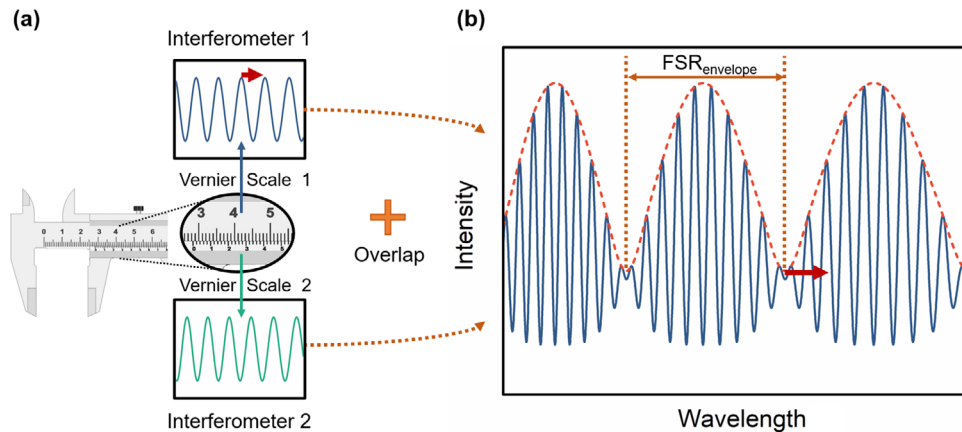


Figure 2. a) Schematic of the optical Vernier effect principle. Like a caliper, the optical analog of the Vernier effect makes use of two scales with different periods (two interferometers with different interferometric frequencies), whose overlap generates a large envelope modulation with enhanced sensing capabilities (larger wavelength shift compared with the individual interferometer, as indicated by the size of the dark red arrows). b) Illustration of an output spectrum resultant from the overlap of two Fabry–Perot interferometers in a parallel configuration.

lishes a comparison between the Vernier envelope modulation and the interference signal from the sensing interferometer. Currently there are two definitions for the M -factor.^[7,12,13] Although distinct, both definitions provide approximately the same result in cases where one of the interferometers is used as a reference.

The first definition of M -factor compares how large the FSR of the Vernier envelope is when compared with the FSR of the individual sensing interferometer. In other words, the M -factor is defined as the ration between the FSR of the Vernier envelope and the FSR of the sensing interferometer. Considering FSR_1 as the FSR of the sensing interferometer, the M -factor is expressed as:^[7,9,14]

$$M = \frac{FSR_{\text{envelope}}}{FSR_1} = \frac{FSR_2}{FSR_2 - FSR_1} \approx \frac{OPL_1}{\delta}. \quad (5)$$

Note that, contrary to the FSR of the Vernier envelope, the M -factor can assume positive or negative values. In this context, a negative M -factor only means that the wavelength shift of the Vernier envelope is in the opposite direction to that of the sensing interferometer.

In practical situations, most of the times it is useful to have a quick estimate of the M -factor. A rough approximation of this value can be performed by assuming that the position of the two consecutive maxima (or minima) of the Vernier envelope are the same as the two consecutive maxima (or minima) of the sensing interferometer signal. Such approximation is useful when dimensioning the sensing and reference interferometers, as the M -factor is approximately dependent on the ratio between the optical path length of the sensing interferometer and the detuning.^[7]

The second definition for the M -factor is intrinsically related to sensing applications. It compares how much the wavelength shift of the Vernier envelope is enhanced (magnified) in comparison to the wavelength shift of the sensing interferometer. In other words, the M -factor is defined as the ratio between the sensitivity of the Vernier envelope (S_{envelope}) and the sensitivity of the sensing interferometer (S_1) to a certain measurand:^[7,12,13]

$$M = \frac{S_{\text{envelope}}}{S_1}. \quad (6)$$

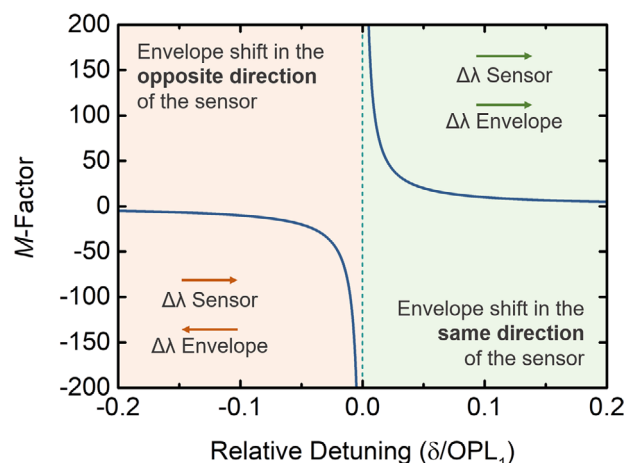


Figure 3. M -factor as a function of the relative detuning (δ/OPL_1), as described in Equation (5). For negative relative detunings, the optical path length of the reference interferometer is larger than that of the sensor interferometer, inducing a negative M -factor. A negative M -factor simply means a Vernier envelope wavelength shift in the opposite direction to that of the sensing interferometer.

Once more, it is worth mentioning that one of the interferometers is considered as a stable reference. If this condition is not verified, the M -factor becomes slightly more complex, as will be discussed in Section 4, and both definitions are no longer equivalent.

The M -factor as a function of the relative detuning between the two interferometers (δ/OPL_1), as in Equation (5), is shown in **Figure 3**. The M -factor trends to infinity as the detuning between the two interferometers approaches zero. In other words, the closer the two interferometers are to an in-tune situation, the higher is the M -factor achieved, and consequently the higher is the sensitivity of the Vernier envelope. On one hand, it is hypothetically possible to achieve extremely high M -factors by making the detuning very small. On the other hand, such small detuning induces a huge Vernier envelope period, since the size of the Vernier envelope also scales inversely with the detuning,

as seen through Equation (4). Large Vernier envelopes might be quite challenging or nearly impossible to measure given the limited range of wavelengths available by the detection system used. Therefore, the maximum M -factor achievable is limited by the maximum size of the Vernier envelope one is able to measure.

Additionally, the small detunings needed to achieve high M -factors can be experimentally challenging to obtain. The errors of current fabrication techniques of micro-interferometers are of the same order as the target detuning required.^[7] Nevertheless, M -factors in the order of tens are constantly being reported, as will be shown in the next section.

3. Configurations and Applications

In the last three years, the fundamental optical Vernier effect became a hot topic in the field of optical fiber sensing. Many distinct optical fiber interferometers were combined with this technique to create sensing devices with enhanced sensitivity capabilities. This section presents an overview of the state-of-the-art configurations and applications using the fundamental optical Vernier effect. The configurations used to introduce the optical Vernier effect are divided in two main groups. The first group consists of configurations containing a single-type of interferometer. The second group is made of hybrid configurations, where two different types of interferometers are combined together. The configurations are presented here without a chronological order and their respective M -factors correspond to the absolute value.

3.1. Single-Type Fiber Configurations

A summary of the sensitivities and M -factors for the different configurations discussed in this section can be found in Table 1 for single-type configurations involving Fabry–Perot interferometers, in Table 2 for the rest of the single-type configurations.

3.1.1. Fabry–Perot Interferometers

The introduction of the optical Vernier effect using FPIs is quite popular, corresponding to almost half of the publications in this topic. The typical configurations are shown in Figure 4. One possibility is to assemble two FPIs in a parallel configuration, as schematized in Figure 4a, by means of a 3 dB fiber coupler. The two FPIs used to introduce the optical Vernier effect have generally similar signal intensities. Therefore, a 3 dB fiber coupler preserves the intensity ratio between the two signals, leading to a Vernier spectrum with high visibility fringes. Nevertheless, other possible split ratios might be useful to consider in order to improve the balance between the intensity of the interfering signals in situations where they are different. In addition to this, purposely inserted losses to one of the interferometers can help reaching a balance between the intensity of the two signals, and therefore improve the visibility of the Vernier spectrum. Alternatively, both FPIs can also be placed in series, as exemplified in Figure 4b, either physically connected or physically separated.

One of the first works employing the optical Vernier effect for optical fiber sensing was reported by Hu et al. in 2012.^[15] They

proposed a sensing structure composed of two FPIs physically connected in a series configuration, as represented in Figure 4b. The first FPI is given by a section of simplified hollow-core fiber (HCF), while the second FPI is a hollow silica microsphere, also forming the tip of the sensing structure. The authors reported the observation of a low frequency envelope modulation in the measured reflected spectrum. Yet, in their publication the authors did not identify the obtained low frequency envelope as being the Vernier envelope. The low frequency envelope achieved a temperature sensitivity of $17.064 \text{ pm } ^\circ\text{C}^{-1}$ between 100 and 1000 °C. Such value is much higher than the one obtained for an individual interferometric peak in the reflection spectrum, which only achieved a sensitivity of $1.349 \text{ pm } ^\circ\text{C}^{-1}$. Today it is known that the cause of such higher sensitivity reached by the low frequency component is the optical Vernier effect.

Two years later, Zhang et al. demonstrated the optical Vernier effect with FPIs in series, but physically separated.^[9] In this case, both interferometers are made of a hollow-core photonic crystal fiber (HC-PCF), separated by a section of single-mode fiber. In this configuration, represented in Figure 4b, one FPI is employed for sensing while the other is taken as a stable reference. The authors used the sensing structure for axial strain and magnetic field sensing. The Vernier envelope reached a strain sensitivity of $47.14 \text{ pm } \mu\epsilon^{-1}$ from 0 to 200 $\mu\epsilon$, corresponding to an M -factor of 29.5. As for magnetic field sensing, the Vernier envelope achieved a sensitivity of 71.57 pm Oe^{-1} from 20 to 35 Oe, with an M -factor of 28.6. For many researchers, this work is seen as the first report of optical Vernier effect in the field of optical fiber sensing.

An extended concept of the optical Vernier effect using physically connected FPIs in a series configuration, but without a reference interferometer was reported in 2020.^[11] The authors also made use of harmonics of the optical Vernier effect to further increase the M -factor and respective sensitivity, as will be discussed later in Section 4. The structure consists of a hollow microsphere (first FPI) followed by a section of a multimode fiber (MMF) (second FPI), and it was applied for strain and temperature sensing. The Vernier envelope achieved a strain sensitivity of $146.3 \text{ pm } \mu\epsilon^{-1}$ from 0 to around 500 $\mu\epsilon$, and a temperature sensitivity of $650 \text{ pm } ^\circ\text{C}^{-1}$ from room temperature up to 100 °C. Simultaneous measurement of strain and temperature was also demonstrated with this structure.

The series configuration with physically separated FPIs seemed very promising however, it only started to enter mainstream use since 2018.^[12,14,16–19] Prior to then, only a few publications with the interferometers physically connected to each other were published.^[20–22] Overall, the optical Vernier effect configurations using only FPIs, the case of two FPIs physically connected in series was the most studied, corresponding to almost half of the publications within this group.^[13,20–30]

The use of FPIs in a parallel configuration was only proposed in 2019, initially by Yao et al.^[31] In their publication, the authors placed a sensing FPI and a reference FPI physically separated by means of a 3 dB fiber coupler, just as schematized in Figure 4a. The sensing interferometer is open, enabling it to be filled by liquids for refractive index sensing. In such case, the Vernier envelope achieved a refractometric sensitivity of $30\,801.53 \text{ nm RIU}^{-1}$ between 1.33347 and 1.33733 RIU. The authors reported an M -factor of 33. Followed by this publication, a few more works were

Table 1. Summary of the optical Vernier effect configurations using single-type Fabry–Perot interferometers.

Year	Configuration	Sensitivity	Range	M	Ref.
2012	SHCF + hollow silica μ sphere	Temperature: 17.604 pm °C ⁻¹	100–1000 °C	N/A	[15]
2014	HC-PCF in series	Strain: 47.14 pm μ e ⁻¹	0–200 μ e	29.5	[9]
2014	HC-PCF in series	Magnetic field: 71.57 pm Oe ⁻¹	20–35 Oe	28.6	[9]
2015	Simplified HCF + SMF	Temperature: 1.019 nm °C ⁻¹	250–300 °C	N/A	[20]
2015	HCF + PCF	Gas RI: 30 899 nm RIU ⁻¹	1.00277–1.00372 RIU	N/A	[21]
2016	HCF + SMF	Airflow: 1.541 nm m ⁻¹ s	3–7 m s ⁻¹	N/A	[22]
2018	HC + ferrule	Temperature: 67.35 pm °C ⁻¹	20–24 °C	23.4	[16]
2018	HCF+SMF + HCF + μ sphere	Temperature: –1.081 nm °C ⁻¹	30–42 °C	N/A	[23]
2018	SMFs in HCF + fusion hole	Gas pressure: 86.64 nm MPa ⁻¹	0–0.6 MPa	32.8	[24]
2018	SMFs in HCF + fusion hole	Temperature: 449 pm °C ⁻¹	40–100 °C	N/A	[24]
2018	HCF + coated LMAF	Hydrogen: –1.04 nm % ⁻¹	0–2.4%	N/A	[14]
2018	SMF in HCF with LC	Temperature: 19.55 nm °C ⁻¹	N/A	N/A	[25]
2019	SCF in parallel	Temperature: 153.8 pm °C ⁻¹	40–220 °C	14.6	[32]
2019	SMFs in HCF	Temperature: 10.28 nm °C ⁻¹	23–25 °C	6.0	[69]
2019	HCF between SMFs	Strain: 18.36 pm μ e ⁻¹	0–320 μ e	14.0	[70]
2019	Milled HCF + SMF	Gas pressure: 80.3 pm kPa ⁻¹	180–220 kPa	N/A	[17]
2019	Milled HCF + SMF	Temperature: –107.0 pm °C ⁻¹	25–65 °C	N/A	[17]
2019	Offset SMF+SMF	Gas RI: –11368.5 nm RIU ⁻¹	1.00003–1.00026 RIU	N/A	[26]
2019	Offset SMF + SMF	Temperature: 98 pm °C ⁻¹	35–65 °C	N/A	[26]
2019	HCF+SMF + Airgap + SMF	Strain: 1.15 nm μ e ⁻¹	0–160 μ e	N/A	[12]
2019	HCF + SMF + Airgap + SMF	Temperature: 3.6 pm °C ⁻¹	50–160 °C	N/A	[12]
2019	Microhole + SMF	RI: 1143.0 nm RIU ⁻¹	1.3352–1.3469 RIU	N/A	[27]
2019	Microhole + SMF	Temperature: –180.5 pm °C ⁻¹	30–90 °C	N/A	[27]
2019	Milled μ sphere in parallel	Salinity: 82.61 nm m ⁻¹	0–0.297 m	6.8	[33]
2019	Milled μ sphere in parallel	RI: 6830.0 nm RIU ⁻¹	1.3176–1.3212 RIU	6.8	[33]
2019	Milled μ sphere in parallel	Temperature –587.37 pm °C ⁻¹	21.7–30 °C	5.1	[33]
2019	HCF partially with PDMS	Temperature: 17.758 nm °C ⁻¹	N/A	27.2	[34]
2019	Fs-laser mirrors in SMF	Strain: 28.11 pm μ e ⁻¹	0–1500 μ e	23.8	[18]
2019	Fs-laser mirrors in SMF	Temperature: 278.48 pm °C ⁻¹	30–100 °C	24.6	[18]
2019	Fs-laser mirrors in SMF	Strain: 145 pm μ e ⁻¹	0–200 μ e	N/A	[19]
2019	Fs-laser mirrors in SMF	Temperature: 927 pm °C ⁻¹	30–60 °C	N/A	[19]
2019	HCF + LMAF	Isopropanol: 20 pm ppm ⁻¹	0–500 ppm	N/A	[28]
2019	HCF + offset SMF in parallel	Strain: –43.2 pm μ e ⁻¹	0–1750 μ e	4.6	[35]
2019	HCF + offset SMF in parallel	Temperature: –27 pm °C ⁻¹	30–100 °C	4.2	[35]
2019	PM-PCF + HC-PCF	Temperature: 535.16 pm °C ⁻¹	24–1000 °C	45	[29]
2019	μ sphere + HCF in parallel	Transverse Load: –3.75 nm N ⁻¹	0–1 N	3.4	[36]
2019	μ sphere + HCF in parallel	Temperature: –3.33 pm °C ⁻¹	50–200 °C	4.2	[36]
2019	HCF in parallel	RI: 30 801.53 nm RIU ⁻¹	1.3347–1.33733 RIU	33	[31]
2019	HCF in parallel	Temperature: 250 pm °C ⁻¹	20–30 °C	N/A	[31]
2019	PCF + HCF partially filled	Humidity: 456 pm %RH ⁻¹	19.63–78.63 %RH	N/A	[13]
2019	FIB-structured MMF TIP	Temperature: –654 pm °C ⁻¹	30–120 °C	>60	[37]
2019	HCF in parallel + Harm.	Strain: 93.4 pm μ e ⁻¹	0–600 μ e	27.7	[7]
2020	HCF filled with DSO	Temperature: 39.21 nm °C ⁻¹	≈35 °C	N/A	[30]
2020	HCF + PM-PCF in parallel	Temperature: –45 pm °C ⁻¹	100–300 °C	3.9	[38]
2020	HCF + PM-PCF in parallel	Temperature: –92 pm °C ⁻¹	300–800 °C	5.3	[38]
2020	H- μ sphere + MMF + Harm.	Strain: 146.3 pm μ e ⁻¹	0–500 μ e	N/A	[11]
2020	H- μ sphere + MMF + Harm.	Temperature: 650 pm °C ⁻¹	22–100 °C	N/A	[11]
2020	Few-mode HCF in parallel	RI: –500 699 nm RIU ⁻¹	1.315027–1.315107 RIU	865	[76]
2021	HCF $\pm$ Harmonics	Gas pressure: 80.8 pm kPa ⁻¹	1–101 kPa	N/A	[71]

Table 2. Summary of the optical Vernier effect configurations using other single-type interferometers.

Year	Configuration	Sensitivity	Range	M	Ref.
2017	MZI: offset spliced SMF	Curvature: -36.26 nm m^{-1}	$0.3\text{--}0.5 \text{ m}^{-1}$	8.0	[10]
2017	MZI: offset spliced SMF	Temperature: $397.36 \text{ pm } ^\circ\text{C}^{-1}$	$10\text{--}75 \text{ }^\circ\text{C}$	8.8	[10]
2018	MZI: MMF + DSHF + MMF	Gas P.: $-63.584 \text{ nm MPa}^{-1}$	$0\text{--}0.8 \text{ MPa}$	7	[43]
2018	MZI: MMF + DSHF + MMF	Temperature: $34.7 \text{ pm } ^\circ\text{C}^{-1}$	$35\text{--}60 \text{ }^\circ\text{C}$	N/A	[43]
2018	MZI: SHTECF	Temperature: $2.057 \text{ nm } ^\circ\text{C}^{-1}$	$25\text{--}30 \text{ }^\circ\text{C}$	48.8	[44]
2018	MZI: MMF with milled air slit	Gas P.: $-82.131 \text{ nm MPa}^{-1}$	$0\text{--}0.7 \text{ MPa}$	9.4	[14]
2018	MZI: MMF with milled air slit	Temperature: $355.2 \text{ pm } ^\circ\text{C}^{-1}$	$25\text{--}100 \text{ }^\circ\text{C}$	10.1	[14]
2019	MZI: spherical-shaped structure	Strain: $-8.47 \text{ pm } \mu\text{e}^{-1}$	N/A	5.4	[39]
2019	MZI: spherical-shaped structure	Curvature: -33.70 nm m^{-1}	N/A	5.4	[39]
2019	MZI: (MMF + HCF + MMF) $\times 2$	Gas P.: $-73.32 \text{ nm MPa}^{-1}$	$0\text{--}0.8 \text{ MPa}$	8.5	[42]
2019	MZI: (MMF + HCF + MMF) $\times 2$	Temperature: $52.60 \text{ pm } ^\circ\text{C}^{-1}$	$30\text{--}100 \text{ }^\circ\text{C}$	8.5	[42]
2019	MZI: coreless + SHF + coreless	RI: $44\,084 \text{ nm RIU}^{-1}$	$1.33288\text{--}1.33311 \text{ RIU}$	3.1	[45]
2019	MZI: MMF + HCF + MMF	Temperature: $528.5 \text{ pm } ^\circ\text{C}^{-1}$	$0\text{--}100 \text{ }^\circ\text{C}$	17.5	[46]
2020	MZI: SMF + FMF + SMF	Static P.: $4.072 \text{ nm MPa}^{-1}$	N/A	N/A	[40]
2020	MZI: SMF + FMF + SMF	Temperature: $1.753 \text{ nm } ^\circ\text{C}^{-1}$	N/A	N/A	[40]
2015	Sagnac: PANDA + PANDA	Temperature: $-13.36 \text{ nm } ^\circ\text{C}^{-1}$	$30\text{--}40 \text{ }^\circ\text{C}$	9.2	[49]
2018	Sagnac: PANDA + Hi-Bi μ -fiber	RI: 2429 nm RIU^{-1}	$1.3320\text{--}1.3369 \text{ RIU}$	5.4	[50]
2018	Sagnac: Coated PMF w/ $^\circ\text{Shift}$	Hydrogen: $-14.61 \text{ nm } \%^{-1}$	$0\text{--}0.8 \text{ } \%$	1.9	[53]
2018	Sagnac: Coated PMF w/ $^\circ\text{Shift}$	Temperature: $-2.44 \text{ nm } ^\circ\text{C}^{-1}$	$30\text{--}60 \text{ }^\circ\text{C}$	15.0	[53]
2019	Sagnac: PANDA w/ $^\circ\text{Shift}$	Strain: $58 \text{ pm } \mu\text{e}^{-1}$	$0\text{--}1440 \text{ } \mu\text{e}$	9.8	[54]
2019	Sagnac: PANDA w/ $^\circ\text{Shift}$	Temperature: $-1.05 \text{ nm } ^\circ\text{C}^{-1}$	$20\text{--}80 \text{ }^\circ\text{C}$	0.8	[54]
2019	Sagnac: Coated PMF w/ $^\circ\text{Shift}$	Isopropanol: 239 pm ppm^{-1}	$0\text{--}42 \text{ ppm}$	4.2	[55]
2019	Sagnac: Coated PMF w/ $^\circ\text{Shift}$	Strain: $53.8 \text{ pm } \mu\text{e}^{-1}$	$0\text{--}365.82 \text{ } \mu\text{e}$	N/A	[55]
2020	Sagnac: PMFs + Push–pull	Strain: $10\,000 \text{ pm } \mu\text{e}^{-1}$	$0\text{--}8 \text{ } \mu\text{e}$	251	[73]
2019	Michelson: DCF + DSHF	Bending: 38.53 nm m^{-1}	$0\text{--}1.24 \text{ m}^{-1}$	N/A	[57]
2019	Michelson: DCF + DSHF	Temperature: $67.2 \text{ pm } ^\circ\text{C}^{-1}$	$50\text{--}130 \text{ }^\circ\text{C}$	N/A	[57]
2019	Michelson: TCF + DSHF	Curvature: 57 nm m^{-1}	$0\text{--}1.14 \text{ m}^{-1}$	N/A	[56]
2019	Michelson: TCF + DSHF	Temperature: $143 \text{ pm } ^\circ\text{C}^{-1}$	$30\text{--}100 \text{ }^\circ\text{C}$	N/A	[56]
2018	Coupler: Hi-Bi coupler	RI: $35\,823.3 \text{ nm RIU}^{-1}$	$1.3330\text{--}1.3347 \text{ RIU}$	N/A	[58]
2020	Coupler: parallel couplers	RI: $114\,620 \text{ nm RIU}^{-1}$	$1.3350\text{--}1.3355 \text{ RIU}$	19.7	[68]
2020	Coupler: parallel couplers	RI: $126\,540 \text{ nm RIU}^{-1}$	$1.3450\text{--}1.3455 \text{ RIU}$	21.7	[68]
2020	Coupler: double helix coupler	RI: $27\,326.59 \text{ nm RIU}^{-1}$	$1.3333\text{--}1.3394 \text{ RIU}$	5.3	[59]
2015	MKR: Cascaded MKR	RI: 6523 nm RIU^{-1}	$1.3320\text{--}1.3350 \text{ RIU}$	N/A	[60]

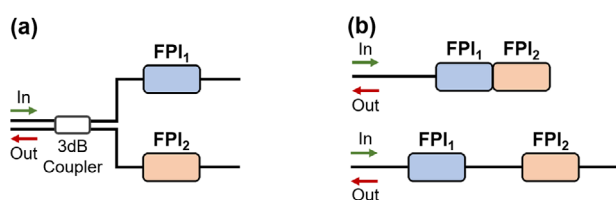


Figure 4. Fabry–Perot interferometer configuration: a) in parallel; b) in series (physically connected or separated).

published using the parallel configuration.^[32–36] The main advantage of the parallel configuration is the possibility of having a reference interferometer without compromising the visibility of the interference signal. The series configuration using two FPIs physically separated, as shown in Figure 4b, may lead to visibility issues due to the presence of an additional interface. In other

words, the amount of light reaching the second FPI is much lower than in the case of two FPI physically connected, or in a parallel configuration as in Figure 4a.

A special case of FPIs in parallel was reported by Gomes et al. in 2019.^[37] The structure consists of a single cavity, where multiple FPI responses are generated due to the different modes co-propagating in the cavity at the same time. The cavity was milled in a tapered multimode fiber probe using focused ion beam. The authors reported a temperature sensitivity of $-654 \text{ pm } ^\circ\text{C}^{-1}$ for the Vernier envelope between 30 and 120 $^\circ\text{C}$.

In terms of applications, the configurations using FPIs were mainly used for temperature^[15,16,20,23,25,29,30,32,34,38] and strain sensing.^[9,12,18,19,35] Apart from these two applications, others such as magnetic field sensing,^[9] gas refractive index,^[21,26] and pressure sensing,^[17,24] airflow sensing,^[22] hydrogen sensing,^[14] humidity sensing,^[13] volatile organic compounds sensing,^[28] and refractive index sensing of liquids^[31] were also reported.

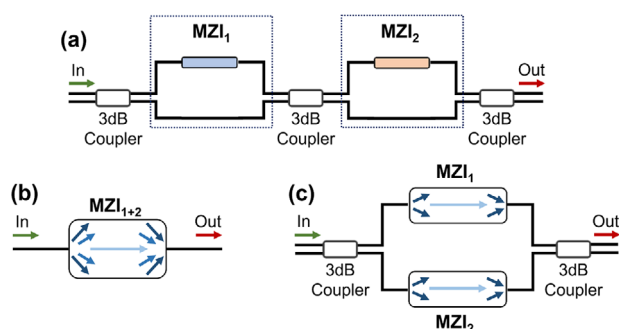


Figure 5. a) Mach-Zehnder interferometers in series. b) Mach-Zehnder interferometers in parallel: b) within the same fiber, or c) physically separated.

Simultaneous measurement of parameters is also possible, combining the response of the Vernier envelope with the individual interferometric peaks from the reflection spectrum. Examples of this are simultaneous measurement of refractive index of liquids and temperature,^[27] simultaneous measurement of salinity and temperature,^[33] or simultaneous measurement of strain and temperature.^[11]

3.1.2. Mach-Zehnder Interferometers

Different types of MZIs can be employed to introduce the optical Vernier effect. **Figure 5** depicts the distinct optical Vernier effect configurations reported in literature using only MZIs.

The first demonstration of optical Vernier effect using MZIs was presented by Liao et al. in 2017.^[10] In their work, the principle of operation was deduced based on two MZIs connected in a series configuration, as represented by **Figure 5a**. Each of the MZIs is a traditional two-path interferometer, where light is divided between two arms with different optical path lengths, recombined at the end and interfering due to the accumulated phase difference. The authors proposed a modified version of the optical Vernier effect, where the envelope is extracted in the frequency domain, rather than performing the traditional curve fitting methods in the wavelength domain. The reported method involves extracting the frequency component correspondent to the Vernier envelope and then applying an inverse fast Fourier transform (IFFT) to retrieve the envelope modulation in the wavelength domain. Experimentally, the MZIs were fabricated by offset splicing single-mode fibers. Keeping one MZI as a reference, the structure was demonstrated for temperature and curvature sensing. For temperature sensing, the Vernier envelope achieved a sensitivity of $397.36 \text{ pm } ^\circ\text{C}^{-1}$ between 10 and 75°C , with an M -factor of 8.8. Regarding curvature sensing, the sensitivity of the Vernier envelope was -36.26 nm m from 0.3 to 0.5 m^{-1} , with an M -factor of 8.0.

Instead of offset spliced fibers, the MZIs can also be fabricated by other means.^[39,40] For example, Lin et al. used a MMF, with a femtosecond laser-machined air cavity, between single-mode fibers,^[41] and Zhao et al. spliced hollow core fibers between MMFs.^[42]

In 2018, a new type of configuration was introduced, represented in **Figure 5b**. The optical Vernier effect is introduced by means of two MZIs in a parallel configuration but integrated

in the same fiber. Lin et al. used a dual side-hole fiber (DSHF) spliced between two pieces of MMF to form such a structure.^[43] In the reported structure, light travels through the core of the DSHF and simultaneously through the two side holes parallel to the core. The authors also opened an access to one of the air holes, allowing for the measurement of gas pressure with a sensitivity of -60 nm MPa^{-1} between 0 and 0.8 MPa. The structure achieved an M -factor of 7. The same type of configuration was demonstrated in a different way by Ni et al. in the same year.^[44] They achieved the same effect by means of a single hole twin eccentric core fiber (SHTECF) spliced between two single-mode fibers, wherein in each splice position, the fiber was collapsed. In this case, the authors used the structure for temperature sensing, obtaining a sensitivity of $2.057 \text{ nm } ^\circ\text{C}^{-1}$ for the Vernier envelope, corresponding to an M -factor of 48.8. In 2019, this configuration was also demonstrated by Hu et al., where the integrated MZI structure consisted of an offset-spliced side-hole fiber (SHF) between two coreless fibers.^[45] The authors applied the proposed sensor for refractive index sensing, reporting a Vernier envelope sensitivity of $44\,084 \text{ nm RIU}^{-1}$ between 1.33288 and 1.33311 RIU, corresponding to an M -factor of only 3.1.

At last, a parallel configuration using two MZIs separated by means of 3 dB fiber couplers, as represented in **Figure 5c** was proposed by Wang et al. in 2019.^[46] In their work, each of the MZIs consists of a simple hollow core fiber spliced between two MMFs. The authors used the structure for temperature sensing, obtaining a sensitivity of $528.5 \text{ pm } ^\circ\text{C}^{-1}$ for the Vernier envelope, between 0 and 100°C . An M -factor of 17.5 was also reported.

3.1.3. Sagnac Interferometers

An optical fiber SI consists of an optical fiber ring, assembled using a 3 dB fiber coupler, in which two beams are propagating in counter directions with different polarization states.^[47] In fiber sensing, a section of polarization maintaining fiber (PMF) is usually placed inside the optical fiber ring, providing different propagating constants along the slow and fast axis. The output signal is given by the interference between the light beams polarized along the slow axis and the fast axis. A polarization controller (PC) is also placed inside the optical fiber ring to adjust the light polarization until the output interference pattern has maximum visibility, given that the polarization state of the input light is unknown. Until 2018, Sagnac interferometers were only used to introduce the optical Vernier effect in a series configuration. The structure typically consists of two fiber rings, each containing a section of PMF as shown in **Figure 6a**. The two PMF sections act as the two interferometers needed to form the optical Vernier effect. Hence, given the birefringence (β) of the PMFs, the optical Vernier effect can be optimized by adjusting the lengths of the PMFs. In this case, the condition that the two optical path lengths must be close is equivalent to $\beta_1 L_1 \approx \beta_2 L_2$.^[48]

In 2015, Shao et al. used a section of a PANDA fiber in both Sagnac interferometers.^[49] In their work, the structure was studied for temperature sensing, while keeping one of the Sagnac interferometers as a stable reference. The authors reported a Vernier envelope sensitivity of $-13.36 \text{ nm } ^\circ\text{C}^{-1}$, achieving an M -factor of around 9.2. Three years later, Wang et al. reported a similar configuration.^[50] However, one of the Sagnac interferom-

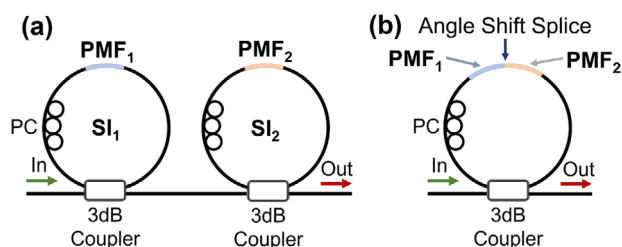


Figure 6. a) Two Sagnac interferometers in series, each containing a polarization maintaining fiber (PMF). b) Single Sagnac interferometer with two PMFs spliced with an angle shift between their fast axes.

eters incorporates a graphene oxide-coated microfiber, while the second contains a PANDA fiber. The presence of the graphene oxide coating induces high birefringence in the microfiber. The authors used the structure for refractive index sensing of liquids, achieving a sensitivity of 2429 nm RIU^{-1} , corresponding to an M -factor of 5.4. The same structure was also demonstrated as a biosensor of bovine serum albumin.

The abovementioned configurations combine the high sensitivity achieved by high-birefringent (Hi-Bi) fibers together with the optical Vernier effect. Nevertheless, similar configurations using only optical fiber rings without employing any PMF were also demonstrated for temperature^[51] and strain sensing.^[52]

An alternative compact version to introduce the optical Vernier effect with Sagnac interferometers was demonstrated in 2018. This new configuration, reported by Wu et al.,^[53] only requires a single Sagnac interferometer ring, as shown in Figure 6b, containing two PMFs spliced with an angle shift between their fast axes. In their work, the authors spliced the two PMFs with a 40° angle shift. One of the PMFs was coated with Pt-load WO_3/SiO_2 powder, which heats up under the presence of hydrogen. The authors reported a temperature sensitivity of $-2.44 \text{ nm } ^\circ\text{C}^{-1}$ for the Vernier envelope. The structure was also explored for hydrogen sensing, achieving a sensitivity of $-14.61 \text{ nm } \%^{-1}$ between 0 and 0.8% of hydrogen. Liu et al. used the same configuration, but with two sections of PANDA fiber spliced with an angle of 45° between their fast axes.^[54] The authors used the structure for strain and temperature sensing. The Vernier envelope attained a strain sensitivity of $58 \text{ pm } \mu\text{e}^{-1}$ from 0 to $1440 \mu\text{e}$, achieving an M -factor of 9.8. Relatively to temperature sensing, the Vernier envelope reached a sensitivity of $-1.05 \text{ nm } ^\circ\text{C}^{-1}$ between 20 and 80°C . The authors also reported simultaneous measurement of strain and temperature using a matrix method. For a completely different application, Wu et al. employed the same configuration for isopropanol measurement.^[55] One of the PMFs was coated with polypyrrole polymer, which swells in the presence of isopropanol, inducing therefore strain in the fiber. The authors reported a sensitivity of 239 pm ppm^{-1} of isopropanol for the Vernier envelope, between 0 and 42 ppm, corresponding to an M -factor of 4.2.

3.1.4. Michelson Interferometers

The Michelson interferometer, similar to Mach–Zehnder interferometer, consists of the interference between light propagating

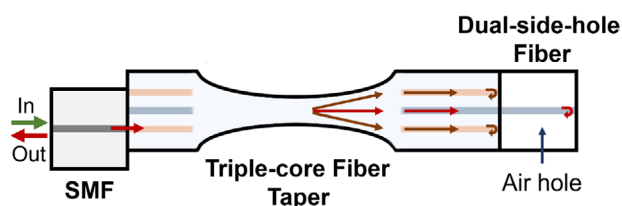


Figure 7. Michelson interferometers in parallel. The structure consists of a tapered triple-core fiber spliced to a dual-side-hole fiber. Adapted from Ref. [56].

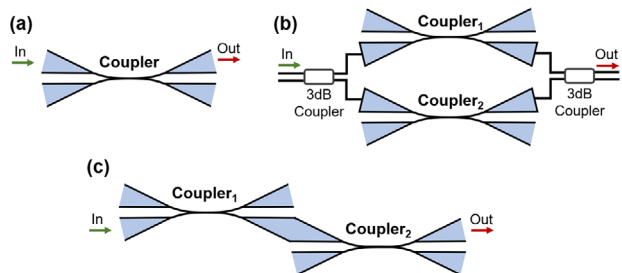


Figure 8. a) Microfiber coupler with birefringence. b) Microfiber couplers in parallel. c) Microfiber couplers in series.

in two arms. However, in a Michelson interferometer, the propagating light is reflected at the end of each arm.^[47]

In 2019, Zhang et al. have shown the introduction of the optical Vernier effect using two juxtaposed fiber Michelson interferometers.^[56] In their configuration, the structure is made of a triple-core fiber (TCF) spliced to a dual-side-hole fiber, as shown in the schematic of Figure 7. The TCF was tapered down, allowing the input light to split between the other two cores. The output signal consists of the interference between the light propagating in the central core and the light propagating in the side cores, where both present slightly different refractive indices. The authors proposed such structure for curvature sensing, achieving a Vernier envelope sensitivity of -57 nm m^{-1} between 0 and 1.14 m^{-1} . The same sensor was also characterized in temperature, where the Vernier envelope obtained a sensitivity of $143 \text{ pm } ^\circ\text{C}^{-1}$ between 30 and 100°C .

Later in that year, the same group proposed a similar device for bending sensing.^[57] However, instead of a TCF, now the authors employed a double-core fiber (DCF) spliced to the dual-side-hole fiber (DSHF) with a slight offset. This offset allows the light traveling in the central core of the DCF to split between the core and the cladding of the DSHF. The authors reported a bending sensitivity of 38.53 nm m from 0 to 1.24 m^{-1} for the Vernier envelope. Regarding temperature sensing, in this case the Vernier envelope reached a sensitivity of $67.2 \text{ pm } ^\circ\text{C}^{-1}$ between 50 and 130°C .

3.1.5. Fiber Coupler Interferometers

A novel way to introduce the optical Vernier effect was proposed by Li et al. in 2018.^[58] The authors have shown the possibility of accomplishing the optical Vernier effect using an optical microfiber coupler, as depicted in Figure 8a. The trick is to make the optical microfiber coupler highly birefringent, causing mode interference between the x and y -polarizations. The structure was

Table 3. Summary of the optical Vernier effect using hybrid-type configurations.

Year	Configuration	Sensitivity	Range	M	Ref.
2019	HCF FPI + MZI	Temperature: $-107.2 \text{ pm } ^\circ\text{C}^{-1}$	$30\text{--}80^\circ\text{C}$	89.3	[61]
2020	FPI + MZI	RI: $-87261.06 \text{ nm RIU}^{-1}$	$1.332\text{--}1.334$	N/A	[62]
2020	FPI + MZI	Temperature: $204.7 \text{ pm } ^\circ\text{C}^{-1}$	$30\text{--}130^\circ\text{C}$	N/A	[62]
2017	Sagnac + FPI	Temperature: $-29 \text{ nm } ^\circ\text{C}^{-1}$	$42\text{--}44^\circ\text{C}$	20.7	[64]
2019	Sagnac + FPI	Sound P: 37.1 nm MPa^{-1}	$62.2\text{--}92.4 \text{ dB}$	N/A	[65]
2019	Sagnac + FPI	Temperature: $10.28 \text{ nm } ^\circ\text{C}^{-1}$	$23\text{--}25^\circ\text{C}$	6.0	[63]
2019	Sagnac + MZI	Strain: $65.71 \text{ pm } \mu\text{e}^{-1}$	$0\text{--}300 \mu\text{e}$	20.8	[67]
2017	MKR + FPI	RI: $311.77\text{--}2460.07 \text{ nm RIU}^{-1}$	$1.3319\text{--}1.3550 \text{ RIU}$	$12\text{--}73$	[66]

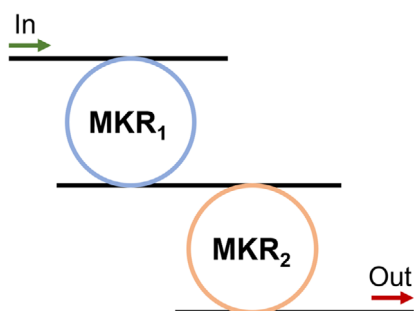


Figure 9. Microfiber knot resonators in series. Adapted from Ref. [60].

used to measure refractive index variations, obtaining a sensitivity of $35\,823.3 \text{ nm RIU}^{-1}$ for the Vernier envelope, at a refractive index around 1.333 RIU . The proof-of-concept of label-free biosensing of human cardiac troponin was also reported with the same proposed structure. This was achieved through functionalization of the optical microfiber coupler with the specific antibody. The sensor achieved a limit of detection of 1 ng ml^{-1} of human cardiac troponin.

Similarly, Chen et al. developed in 2020, a double helix microfiber coupler, which is inherently highly birefringent, introducing therefore the optical Vernier effect.^[59] The authors also used the device to sense variations of refractive index, reporting a Vernier envelope sensitivity of $27\,326.59 \text{ nm RIU}^{-1}$ between 1.3333 and 1.3394 RIU , achieving an *M*-factor of around 5.3 .

Recently, Jiang et al. have discussed the possibility of introducing the optical Vernier effect with two optical microfiber couplers in a parallel configuration, as shown in the schematic of Figure 8b, or in a series configurations, as in Figure 8c. The authors demonstrated ultra-high sensitivity to refractive index with the parallel configuration, where the Vernier envelope reached a sensitivity of $114\,620 \text{ nm RIU}^{-1}$ between 1.3350 and 1.3355 RIU , corresponding to an *M*-factor of 19.7 . Moreover, the Vernier envelope also achieved a sensitivity of $126\,540 \text{ nm RIU}^{-1}$ in a refractive range between 1.3450 and 1.3455 RIU , corresponding to an *M*-factor of 21.7 .

3.1.6. Microfiber Knot Resonators

The combination of microfiber knot resonators (MKRs) and the optical Vernier effect was proposed by Xu et al. back in 2015.^[60]

In their work, two MKRs were fabricated and assembled in series, as depicted in the schematic of Figure 9. The radius of both microfiber knot resonators is slightly different, achieving, therefore, slightly different resonant frequencies. One of the MKRs was taken as a stable reference, while the other was used for refractive index sensing of liquid solutions. The authors reported a Vernier envelope sensitivity of 6523 nm RIU^{-1} between 1.3315 and 1.3349 RIU , achieving a refractive resolution of $1.533 \times 10^{-7} \text{ RIU}$.

3.2. Hybrid-Type Fiber Configurations

A comparison between the different reported sensors using hybrid-type fiber configurations is presented in Table 3.

3.2.1. Fabry–Perot Interferometer with Mach–Zehnder Interferometer

The combination between a FPI and a MZI was introduced by Ying et al. in 2019.^[61] In their publication, the authors make use of the MZI as a tool to demodulate the FPI response, through the optical Vernier effect. Figure 10 presents a schematic of the proposed configuration, where an MZI is incorporated in the structure, right before the signal reaches the output. The FPI consisted of a hollow-core fiber spliced between two single-mode fibers, while the MZI is a traditional configuration composed of two 3 dB fiber couplers and different arm lengths. The optical path difference between the two arms of the MZI needs to be adjusted to closely match the optical path length of the FPI. The authors proposed the structure for temperature sensing, using the FPI as the sensing interferometer and the MZI as the reference interferometer. A temperature sensitivity of $-107.2 \text{ pm } ^\circ\text{C}^{-1}$ between 30 and 80°C was reported for the Vernier envelope. According to the authors, the sensor achieved a high *M*-factor of 89.3 .

One year later, Li et al. proposed a similar configuration, where the FPI and the MZI are composed of a single-mode fiber spliced between two other similar fibers, but with a core-offset.^[62] The core offset of the central fiber is large ($80 \mu\text{m}$) for the FPI, creating therefore an open-air cavity. As for the MZI, the central fiber core offset is slightly smaller ($62.5 \mu\text{m}$) so that light travels through air and also through the cladding of the central fiber, forming the two arms of the interferometer. The authors demonstrated and applied a new concept of enhanced Vernier effect to

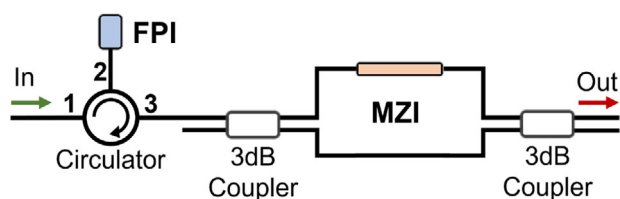


Figure 10. Combination of a Fabry–Perot interferometer (FPI) in series with a Mach–Zehnder interferometer (MZI). Adapted from Ref. [61].

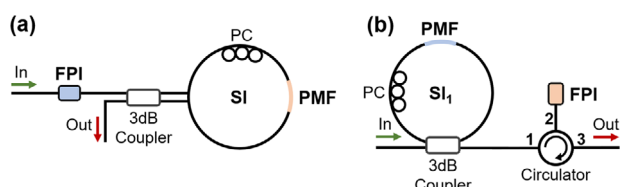


Figure 11. Combination of a Fabry–Perot interferometer (FPI) in series with a Sagnac interferometer (SI). a) FPI used in transmission. b) FPI applied in reflection.

further increase the final sensitivity, as will be discussed later in Section 4.

3.2.2. Sagnac Interferometer with Fabry–Perot Interferometer

FPIs were also combined with fiber SIs in a hybrid configuration to introduce the optical Vernier effect. In 2019, Zhou et al. explored a configuration similar to the one represented in **Figure 11a**, where an FPI is introduced before an SI, without the need of an optical circulator.^[63] However, in this case the FPI is not made out of an optical fiber structure, but rather by two collimators and a quartz wave plate coated with reflective coating on both ends, acting as the reference interferometer. The SI is made of optical fiber and contains a section of a polarization maintaining PANDA fiber. Temperature sensing was performed by changing the temperature from 23 to 25 °C around the SI. The authors reported a sensitivity of 10.28 nm °C^{−1} for the Vernier envelope, corresponding to an *M*-factor of 6.0.

A similar hybrid configuration can also be realized using an optical circulator to embed the response of the FPI in reflection, as shown in **Figure 11b**. Such configuration was initially reported by Yang et al. in 2017.^[64] The SI contains a section of a PANDA fiber and the FPI consists of a silica capillary tube between two single-mode fibers. The structure was also demonstrated for temperature sensing. The authors placed both sensors inside a furnace, changing the temperature of both simultaneously. This approach is not the traditionally adopted, since none of the interferometers is used as a reference, which will be discussed later in Section 4. Nevertheless, in the authors approach, the FPI has much lower temperature sensitivity compared with the SI, and therefore it can be assumed approximately as a reference. Therefore, within the short temperature range reported in the publication (between 42 and 44 °C), the temperature effect on the FPI can be negligible. The authors reported a temperature sensitivity of −29.0 nm °C^{−1} for the Vernier envelope, achieving an *M*-factor of around 20.7.

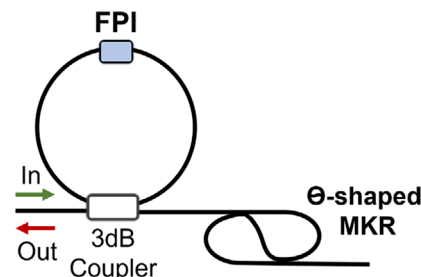


Figure 12. Combination of a Fabry–Perot interferometer (FPI) in series with a Θ-shaped microfiber knot resonator (MKR). Adapted from Ref. [66].

Two years later, Wang et al. demonstrated an equivalent configuration for acoustic sensing.^[65] The SI contains a section of a dual-core photonic crystal fiber and acts as the reference interferometer. The Fabry–Perot interferometer is tunable and contains a polymer film that slightly deforms in the presence of vibrations. The authors reported a maximum sound pressure sensitivity of 37.1 nm Pa^{−1} between 0 and approximately 0.6 Pa, for the Vernier envelope.

3.2.3. Microfiber Knot Resonator with Fabry–Perot Interferometer

In 2017, Xu et al. developed a Θ-shaped MKR combined with a FPI to introduce the optical Vernier effect with tunable properties.^[66] The structure is monitored in a reflection configuration, where the Θ-shaped MKR is connected to the FPI by means of a 3 dB fiber coupler, as seen in **Figure 12**.

The FPI is a commercially available device and the Θ-shaped MKR was fabricated using optical microfibers. The authors demonstrated the possibility of tuning the *M*-factor obtained through the optical Vernier effect by simply changing the diameter of the Θ-shaped MKR. With this, the final sensitivity of the Vernier envelope can be adjusted depending on the applications. In their work, the structure was used to sense refractive index variations around the Θ-shaped MKR, obtaining a Vernier envelope sensitivity that can be tuned from 311.77 to ≈ 2460.07 nm RIU^{−1}, corresponding to an *M*-factor changing from 12 to around 73.

3.2.4. Sagnac Interferometer with Mach–Zehnder Interferometer

In 2019, Liu et al. demonstrated the optical Vernier effect introduced through the combination of a SI with a MZI in a series configuration,^[67] described by **Figure 13**. The SI contained a section of a PANDA fiber and acted as the reference interferometer. The MZI was made of a section of a few-mode fiber spliced between two single-mode fibers, with a slight core-offset at the input to excite more than just the fundamental mode. Therefore, the MZI can be interpreted as a modal interferometer. The authors studied the response of the sensor to strain, obtaining a sensitivity of 65.71 pm με^{−1} between 0 and 300 με for the Vernier envelope. The authors reported an *M*-factor of 20.8.

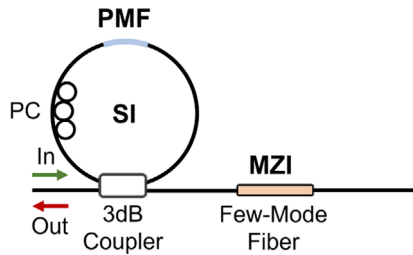


Figure 13. Combination of an SI with a Mach-Zehnder interferometer (MZI). Adapted from Ref. [67].

4. Extended Concepts of the Optical Vernier Effect

4.1. Complex Optical Vernier Effect

The traditional optical Vernier effect requires that one of the interferometers is taken as a stable reference. Under such conditions, the two definitions for the M -factor presented previously (Equations (5) and (6)) provide the same result, and therefore are equivalent. However, there are some cases where it is not feasible to maintain one of the interferometers as a reference. The measurand is then affecting both interferometers of the configuration simultaneously.

In this complex case of optical Vernier effect, both interferometers must be considered as a combined sensing structure. Hence, one expects that the M -factor and respective sensitivity of the Vernier envelope will depend on the response of both interferometers. This can lead to distinct scenarios which include a decrement of the envelope sensitivity (called reduced optical Vernier effect) or, in contrast, to an enhancement of the envelope sensitivity (called enhanced optical Vernier effect).

4.1.1. Sensitivity of the Vernier Envelope

In the presence of no specific reference interferometer, both interferometers of the system act as sensors. The sensitivity of the Vernier envelope, in this situation, is defined as:^[11]

$$S_{\text{envelope}} = \frac{OPL_1}{OPL_1 - OPL_2} S_1 - \frac{OPL_2}{OPL_1 - OPL_2} S_2, \quad (7)$$

where OPL_1 and OPL_2 are the optical path lengths of the first and second interferometer, respectively, and S_1 and S_2 are the individual sensitivities of the first and second interferometer, respectively, to the measurand. Expressed in terms of the free spectral ranges (FSRs) of both interferometers, the sensitivity of the Vernier envelope can also be defined as:^[62]

$$S_{\text{envelope}} = \frac{FSR_2}{FSR_2 - FSR_1} S_1 - \frac{FSR_1}{FSR_2 - FSR_1} S_2 = M_1 S_1 - M_2 S_2, \quad (8)$$

where the ratios between the FSRs correspond to the respective M -factors defined in Equation (5). M_1 is then the M -factor for the interferometer 1, as if the interferometer 2 was considered as a reference, and M_2 is the M -factor for the interferometer 2,

in a situation where the interferometer 1 would be considered a reference.

As seen from Equation (8), the sensitivity of the Vernier envelope depends on the difference between the sensitivities of the two interferometers of the system, but weighted by their respective M -factor. This property leads to three distinct outcomes:^[11,48,62] (1) if the two interferometers present similar sensitivities with the same signal (i.e., both positive or both negative) and similar M -factors, the difference between their responses would practically cancel each other out, according to Equation (8), leading to a Vernier envelope with a very small or even null sensitivity, usually referred to as reduced optical Vernier effect; (2) if one of the interferometers is considerably more sensitive than the other, but both sensitivities have the same sign (i.e., both positive or both negative), the difference in Equation (8) can still be large and the Vernier envelope may still present a magnified sensitivity. However, the Vernier envelope sensitivity would still be smaller in comparison to the case of having a specific reference interferometer; (3) if both interferometers have opposite sensitivities (i.e., one positive and the other negative), the difference in Equation (8) is converted into a sum. Therefore, the Vernier envelope will present an enhanced sensitivity resulting from the sum of the magnified sensitivities from the two interferometers. Such a case is normally referred to as enhanced optical Vernier effect.

Naturally, the last case where the two interferometers have opposite sensitivities is the most remarkable one, since an additional sensitivity contribution is making the Vernier envelope achieve higher sensitivities than the traditional case of considering a reference interferometer. Developing a structure with enhanced Vernier effect can be challenging, as one needs to find two interferometers with opposite responses to the parameter to be measured. In this context, hybrid-type fiber configurations more easily fulfill such requirements by offering more flexibility in the diversity of interferometers that can be combined.

4.1.2. Applications of the Complex Vernier Effect

The case of one interferometer having more sensitivity than the other (case (2)) can be found in the work of Yang et al. explored in Section 3.2.2.^[64] The authors placed both sensors, a FPI and a SI inside a furnace, changing the temperature of both simultaneously. In this situation, no specific reference interferometer is used and both interferometers are affected by the temperature variations. However, in the authors' approach, the FPI has much lower temperature sensitivity compared with the SI. Hence, within the short temperature range used (between 42 and 44 °C), the temperature effect on the FPI can be negligible and the Vernier envelope still shows magnified sensitivity. A similar case was also presented by Gomes et al. in 2020.^[11] As seen in Section 3.1.1, the authors combined two FPIs physically connected in series, where one of the FPIs is a hollow microsphere and the other is a section of a multimode fiber. On one hand, for strain sensing the hollow microsphere has considerably higher strain sensitivity compared with the section of multimode fiber, due to its inherent structure and mechanical properties. On the other hand, the multimode fiber has higher temperature sensitivity than the hollow microsphere, since the last mainly consists of air.

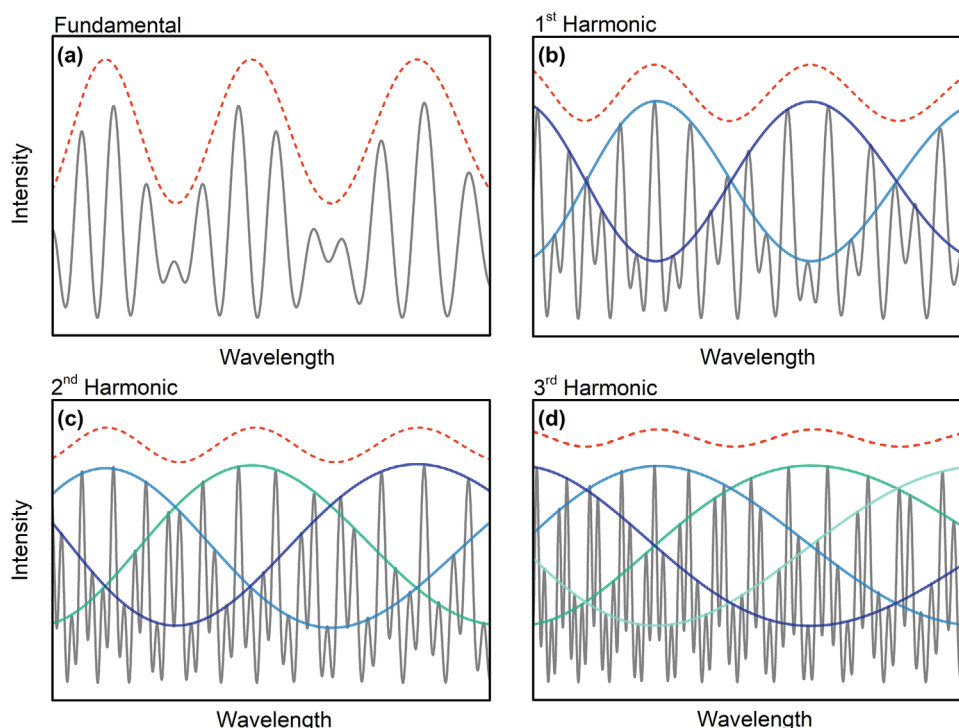


Figure 14. Illustration of output spectra for different harmonic orders: a) fundamental case ($i = 0$), b) 1st harmonic ($i = 1$), c) 2nd harmonic ($i = 2$), and d) 3rd harmonic ($i = 3$). The upper Vernier envelope is marked with a dashed line and was shifted upwards to be distinguishable from the internal Vernier envelopes, marked with blue line. Adapted under the terms of the CC-BY license.^[7] Copyright 2019, The Authors, published by MDPI.

Therefore, the Vernier envelope also showed magnified sensitivity to strain, mainly dependent on the performance of the hollow microsphere, and also magnified sensitivity to temperature, mainly dependent on the performance of the multimode fiber.

The enhanced Vernier effect (case (3)) was reported by Li et al. in 2020.^[62] As discussed in Section 3.2.1, the authors combined an FPI with a MZI for refractive index sensing. In their work, the authors presented and demonstrated the enhanced Vernier effect, where both interferometers act as sensors and present opposite sensitivities to the measured parameters. With this, the authors have shown that the Vernier envelope sensitivity can be further improved, beyond the traditional case of Vernier effect. The Vernier envelope achieved a refractive index sensitivity of $-87261.06 \text{ nm RIU}^{-1}$ between 1.332 and 1.334. Moreover, the temperature response was also evaluated, where a sensitivity of $204.7 \text{ pm } ^\circ\text{C}^{-1}$ between 30 and 130°C was also reported.

4.2. Optical Harmonic Vernier Effect

Until recently, researchers thought that the application of the optical Vernier effect would necessarily require the use of two interferometers with slightly detuned interferometric signals (small difference in optical path lengths). However, Gomes et al. have demonstrated the possibility to use two interferometers with very different interferometric signals (i.e., with very different optical path lengths).^[7] This extended concept is known as the optical harmonic Vernier effect. With this, a complex harmonic response is generated with enhanced sensing resolution and sensing mag-

nification capabilities when compared with the fundamental case explored until now.

The introduction of harmonics to the optical Vernier effect happens when the OPL of the reference interferometer (here denoted as interferometer 2) is increased by multiple integers (i -times, i being the harmonic order) of the OPL of the sensing interferometer, ideally maintaining the detuning. Mathematically, this relationship is described as:^[7]

$$OPL_2 = (i + 1) OPL_1 - \delta, \quad (9)$$

where i is the harmonic order and δ is the detuning between the OPLs of the two interferometers. The fundamental case, as described by Equation (2), is then a specific of Equation (9), where $i = 0$.

Increasing the OPL of the reference interferometer generates an interference signal with higher frequency (smaller FSR). From a different perspective, comparing with a caliper, it is equivalent of making one of the Vernier scales finer, which will result in an improved measurement. **Figure 14** illustrates the output spectra for the fundamental case and for the first three harmonic orders of the optical Vernier effect.

4.2.1. Properties

Free Spectral Range: With the new dimensioning of the reference interferometer, one can now refer to its FSR as FSR_2^i , as a function of the harmonic order " i ". Gomes et al. have demonstrated that the FSR of the upper Vernier envelope is the same

for every harmonic order, if the detuning δ is preserved.^[7] This is known as the regeneration property, where the FSR of the upper envelope is defined as:^[7]

$$FSR_{\text{envelope}}^i = \left| \frac{FSR_2^i FSR_1}{(i+1) FSR_2^i - FSR_1} \right|, \quad (10)$$

which is an extended version of Equation (4). Such property is visible in Figure 14, where the upper Vernier envelope is marked with a dashed line.

Apart from the upper Vernier envelope, internal Vernier envelopes can be traced by fitting groups of peaks,^[7] as visible by the blue lines in Figure 14. Contrary, to the upper Vernier envelope, the size of the internal Vernier envelopes scales with the harmonic order “ i ”. Hence, the FSR of the internal Vernier envelopes, for a parallel configuration, is expressed as:^[7]

$$FSR_{\text{internal envelope}}^i = \left| \frac{(i+1) FSR_2^i FSR_1}{(i+1) FSR_2^i - FSR_1} \right| = (i+1) FSR_{\text{envelope}}^i, \quad (11)$$

considering that the detuning parameter (δ) is the same for every harmonic order. For the case of a series configuration, additional factors might have to be taking into consideration.^[7]

The intersection points between internal Vernier envelopes provide multiple points useful to monitor the wavelength shift. The error of fitting and tracking the internal envelope intersections is, in general, smaller than fitting and tracking the maxima (or minima) of the upper Vernier envelope.^[7]

Magnification Factor (M -Factor): One of the great potentials of using harmonics of the optical Vernier effect is the further enhancement of the M -factor with increasing harmonic order. Although the size of the upper Vernier envelope is constant for every harmonic order with the same detuning, as seen before, the M -factor increases linearly with the harmonic order. As demonstrated by Gomes et al., the M -factor can be defined in a more general way as:^[7]

$$M^i = (i+1) M = (i+1) \frac{FSR_{\text{envelope}}^i}{FSR_1}, \quad (12)$$

where M^i is the M -factor for the harmonic order i , and M is the M -factor for the fundamental case expressed by Equation (5).

Figure 15 represents the M -factor as a function of the relative detuning (δ/OPL_1) between the two interferometers for different harmonic orders. It is evident that the M -factor curve broadens for higher harmonic orders; essentially it is easier to achieve higher M -factors, even for larger detunings. Moreover, for the same relative detuning, the M -factor increases linearly with the harmonic orders, according to Equation (12).

4.2.2. Applications of the Optical Harmonic Vernier Effect

When the optical harmonic Vernier effect was introduced in 2019, its properties were demonstrated using FPIs in a parallel configuration.^[7] The authors used simple hollow capillary tubes spliced between two sections of single-mode fiber to form the

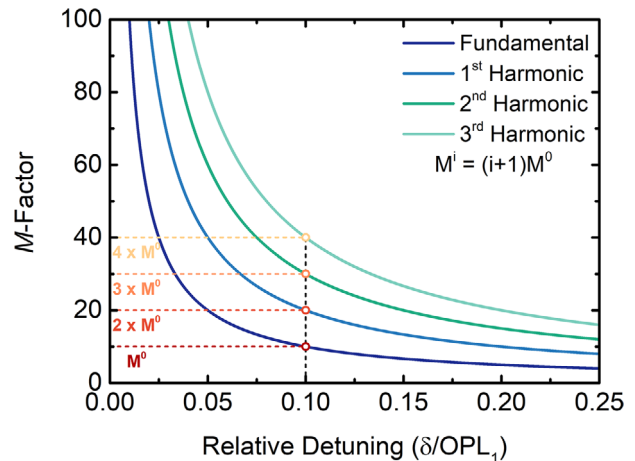


Figure 15. M -factor as a function of the relative detuning (δ/OPL_1) for different harmonic orders, as described in Equation (12). For the same relative detuning, the M -factor increases linearly with the harmonic order: $M^i = (i+1) M^0$, where M^0 is the M -factor for the fundamental case. Adapted from the terms of the CC-BY license.^[7] Copyright 2019, The Authors, published by MDPI.

FPIs. The two FPIs were separated by means of a 3 dB fiber coupler and characterized in terms of applied strain. Strain was only applied to the sensing FPI, while the reference FPI was switched between 3 FPIs with distinct cavity lengths to introduce the first three harmonic orders. Since experimentally, it is extremely difficult to fabricate FPIs with the exact same detuning, the three different harmonic orders were compared by means of a compensated phase sensitivity, where the typical sensitivity to strain was divided by the respective FSR of the envelope, eliminating the influence of the detuning. The authors reported a compensated sensitivity and respective M -factor that increases proportionally to the harmonic order. Moreover, the authors also demonstrated the equivalence between Equations (6) and (12). In terms of strain sensitivity, a maximum sensitivity of $93.4 \text{ pm } \mu\epsilon^{-1}$ for the Vernier envelope was reported using the 2nd harmonic with a detuning of $-5 \text{ } \mu\text{m}$.

The use of optical harmonics of the Vernier effect for a series configuration was only reported in 2020, also by Gomes et al.^[11] As previously discussed in Sections 3.1.1 and 4.1.2, the authors used two FPIs physically connected in series to introduce the first harmonic of the Vernier effect together with a special case of optical Vernier effect where none of the interferometers is used as a specific reference.

Later in 2020, Robalinho et al. reported the application of harmonics of the optical Vernier effect to fiber loop mirrors for strain sensing.^[48] In their work, the authors used two fiber loop mirrors in a parallel configuration, each of them containing a different type of PMF. The PMFs were chosen in a way that the two fiber loop mirrors present opposite sensitivity to strain, introducing therefore the enhanced Vernier effect case, discussed in Section 4. The authors have compared the fundamental case with the 1st harmonic, demonstrating that the increase of sensitivity with the harmonic order is also valid for fiber loop mirrors, and not just for configurations using FPIs. Moreover, the authors have demonstrated that, in this specific case of enhanced Vernier effect, the carrier signal is actually constant as

a function of the applied strain, while the envelope modulation shifts with enhanced sensitivity.

Early in 2021, Yang et al. have used harmonics of the optical Vernier effect with FPIs for gas pressure sensing.^[71] The authors reported a sensitivity of 80.8 pm kPa⁻¹ from 1 to 101 kPa using the first harmonic.

5. Final Remarks

The optical Vernier effect has the ability to magnify the wavelength shift of the Vernier envelope and brings new opportunities to fabricate highly sensitive sensors with, ultimately, improved resolution compared to that available with more conventional interferometers. By tailoring the characteristics of the interferometers, the optical Vernier effect can be maximized to achieve high magnification factors. However, one needs to be careful and analyze, for each case, if such high *M*-factors are experimentally feasible, given the restrictions of the setup available. The higher the *M*-factor achieved, the larger is the Vernier envelope. Therefore, there is a maximum size of the Vernier envelope period for which the detection system is able to track and measure. This imposes a limit in the maximum *M*-factor achievable with this effect.

This review paper explored the different types of configurations and interferometers used to introduce the optical Vernier effect. These configurations may involve just a single type of interferometer or, alternatively, it can combine distinct types of interferometers in a hybrid structure, together with additional advantages. For more detailed applications of the optical Vernier effect using optical fiber sensors, please consider the report of Liu et al. from 2021.^[72]

Single-type fiber configurations are simpler, in the way that one must only deal with a unique type of interferometer, and therefore the fine tuning of the structures can be easier and straightforward. On the contrary, dealing with hybrid-type fiber configurations implies knowing the response of two distinct interferometers and the fine tuning of their optical path lengths can, in some cases, be quite challenging. Nevertheless, hybrid-type fiber configurations stand out for their flexibility and higher *M*-factors achievable, especially for allowing the implementation of the enhanced case of optical Vernier effect, as discussed in Section 4.

The *M*-factors reported range from values as low as 1.9 (such as the coated Sagnac interferometer for hydrogen sensing^[53]) to high values such as 89.3 (in case of a hybrid structure combining an FPI with an MZI for temperature sensing^[61]). Single-type configurations using FPIs have typically *M*-factors between 10 and 30. Interestingly, MZI configurations and configurations using Sagnac interferometers have, in general, lower *M*-factors, with values normally below 10. Some publications do not provide the *M*-factor or enough data to estimate it. Nevertheless, one can observe that the sensitivities obtained are higher than those normally obtained for such type of sensors without the optical Vernier effect, for instance, the ability of reaching a new order of magnitude in refractive index sensing with a sensitivity of 126 540 nm RIU⁻¹.^[68]

The special case, where no specific reference interferometer is used, can lead to an enhanced Vernier effect, if both interferometers have opposite sensitivities to the measured parameter. The result is a Vernier envelope whose sensitivity depends on the sum

between the responses of the two interferometers, providing additional magnification compared with the case that considers a reference interferometer.

The recently reported optical harmonic Vernier effect was also explored. By upscaling the optical path length of the reference interferometer, additional frequencies are added to the final response, leading to a complex Vernier output spectrum with harmonic properties. The *M*-factors obtained increase linearly with the harmonic order *i*. Hence, the proposed concept is a way to overcome the limitations of the fundamental effect, allowing the reaching of new *M*-factors enhanced by (*i* + 1) times. The use of such effect has already demonstrated capabilities of reaching new records of sensitivity, for instance in strain sensitivity (10 000 pm με⁻¹), as reported by Robalinho et al.^[73] Moreover, non-conventional interferometers combined with optical harmonics of the Vernier effect are also presently being studied, aiming to employ this effect for more specific applications, such as the development of nano-displacement sensors.^[74,75]

There is still quite some space for further improvements and developments in this area. Alternative ways of going beyond the limitations of the optical Vernier effect are currently being explored. An example is the recent work of Gomes et al., where the authors showed that it is possible to combine the optical Vernier effect with mode interference, reaching *M*-factors an order of magnitude higher than what could be reached until now.^[76] Moreover, the method preserves a measurable Vernier envelope, whilst achieving extremely high *M*-factors. The authors reported a record *M*-factor of over 850 and a giant refractive index sensitivity of about 500 000 nm RIU⁻¹.

Hence, the trend is to explore further the limits of high resolution sensing applications, for instance toward nanostrain or microkelvin measurements.^[75,77] Moreover, there is also the opportunity to explore complex sensors that multiplex the optical Vernier effect, or combines it with other kinds of sensing structures, such as fiber Bragg gratings (FBGs).^[78]

At last, a huge downside of the optical Vernier effect, that still requires quite some investigation, is the interrogation system. There is an urgent need for the development of a simpler interrogation system to analyze the response of the effect. The need of a broadband source and an optical spectrum analyzer to measure a broad range of wavelengths, plus the additional signal processing required to extract the Vernier envelope wavelength shift from the spectrum, makes the use of this effect challenging. If there was an interrogation system relying only on photodetectors and two, or a few more, laser lines to measure and characterize in a simpler, faster, and cheaper way the response of the optical Vernier effect, it would represent a huge step toward the acceptance and quick adoption of the optical Vernier effect as a viable sensing solution in different areas.

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Conflict of Interest

The authors declare no conflict of interest.

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