

Optoelectronic Oscillator for Physical Length Measurement of PMMA Plastic Optical Fibers

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Abstract — To the best of the authors' knowledge, this work presents the first demonstration of a nonconventional, simple, and low-cost optoelectronic oscillator (OEO) configuration for measuring the physical length of step-index polymethyl methacrylate (PMMA) plastic optical fibers (POFs). The technique is based on measuring the OEO free-spectral range (FSR). Calibration curves were obtained for two OEO loop configurations using POF samples with physical lengths ranging from 0.15 to 46.07 m. An unknown-length POF, which was not used for calibration, was estimated to be 14.82 m from the curve of the original configuration; subsequent measurement with a ruler yielded 14.67 m, corresponding to a relative error of approximately 1%.

Keywords — Optoelectronic oscillator, plastic optical fiber, PMMA, free spectral range, length measurement.

I. INTRODUCTION

Optoelectronic oscillators (OEOs) have been widely investigated because of their ability to generate radio-frequency (RF) carriers with high spectral purity when continuous-wave (CW) light is launched into the oscillation loop [1]. In this loop, propagation occurs partly in the optical domain, mainly through an optical fiber, and partly in the electrical domain, through transmission lines. A conventional OEO is typically based on singlemode silica fibers and can generate RF carriers in the multi-GHz range with low phase-noise, largely independent of the central oscillation frequency. The already reported applications of OEOs include low-phase-noise microwave generation, clock recovery, timing-reference generation, radio-over-fiber systems, radar, microwave photonic communications, and microwave photonic sensing [1]. OEOs can also be used for optical-length, distance, and displacement measurements while avoiding the 2π -phase ambiguity characteristic of interferometric systems [2–4].

OEOs based on multimode fibers or light-emitting diodes (LEDs) are still unconventional, particularly when implemented with PMMA POFs, as reported in [5] for educational puposes. POFs are used in short-range links and networks, as well as in automotive, industrial, and sensing applications [6]. Length measurement of optical fibers can be performed using well known techniques such as optical time-domain reflectometry (OTDR), interferometry, and ring-laser-based systems. Although these approaches may provide high resolution or long range, they generally require laser sources, fast photodetectors, or specialized instrumentation [7,8]. OTDRs dedicated to POF characterization, including fiber-length measurement, remain

relatively rare on the market compared with conventional OTDRs designed for silica fibers [9]. In the reviewed literature, OEO-based metrological applications predominantly employ lasers, singlemode silica fibers, and higher-speed optoelectronic components [2–4]. Although an earlier study demonstrated oscillation using visible LEDs and POFs [5], to the best of our knowledge, no prior or subsequent work has reported the use of this configuration to determine the physical length of PMMA SI-POFs from an FSR calibration curve. This apparent gap in the literature highlights the distinct contribution of the present work.

This paper proposes and demonstrates the use of an OEO in a nonconventional, simple, and low-cost configuration comprising an LED as the optical source and a segment of step-index POF (SI-POF) as the optical section of the loop. The LED was selected because of its low cost, wide availability, coupling compatibility with the 1-mm POF core, and direct-modulation capability, which eliminates the need for an external electro-optic modulator. Conversely, its limited bandwidth introduces frequency-dependent attenuation and phase delay. A calibration curve enables the physical length L of an unknown POF to be determined from the FSR of the assembled OEO.

The remainder of this paper is organized as follows. Section II describes the experimental setup. Section III presents the physical model. Section IV presents the experimental results and discussion. Finally, Section V presents the conclusions.

II. EXPERIMENTAL SETUP

Figure 1 shows a schematic diagram of the benchtop OEO experimental setup, while Figure 2 presents a photograph of the assembled system.

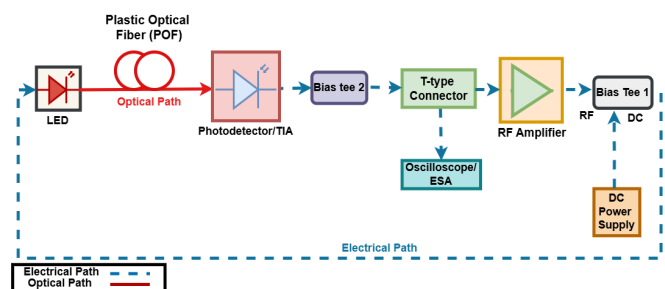


Fig. 1. Schematic diagram of the experimental setup, including the power divider and the optical, electrical, bias, and measurement paths.

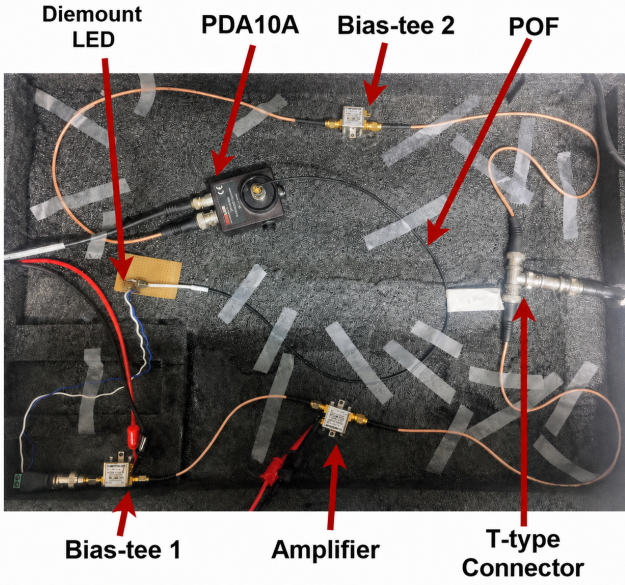


Fig. 2. Photograph of one of the OEO setups assembled in the laboratory.

A 650-nm Hyper-Red LED from Diemount [10] was used as the optical source. Its output was directly coupled to a PMMA SI-POF segment of length L . The light emerging from the POF was detected by a Thorlabs PDA10A photodetector equipped with a 5-k Ω transimpedance amplifier (TIA) and a 150-MHz bandwidth. The electrical signal passed through a DC block (Bias-tee 2) and was then amplified by a Mini-Circuits RF amplifier with a nominal gain of 20 dB and a specified frequency range from 20 MHz to 4 GHz. The T-type connector splits the signal between the measurement branch and the feedback branch. The output was split between an oscilloscope or electrical spectrum analyzer (ESA), and the feedback branch. Such feedback which returns to the LED through Bias-tee 1, it is combined with the DC bias. Although the amplifier bandwidth is much wider than the oscillation-frequency range of interest, its gain and phase response at the frequencies actually used affect the oscillation condition. A lower-bandwidth amplifier could be used provided that it supplied sufficient gain and did not attenuate the adjacent modes required for FSR determination. The bias supply connected to Bias-tee 1 was adjusted to approximately 2.1 V and 320 mA. The electrical cables used in the loop had an approximate total length of 0.6 m. Optical coupling among the LED, the POF, and the photodetector was achieved by directly aligning their end faces to maximize the detected signal level.

A second measurement series was performed after modifications to the OEO feedback loop. In this configuration, the total electrical-cable length was reduced, and the original amplifier was replaced with a Zeenko ZK04-UM low-noise amplifier with a nominal operating range from 100 kHz to 4 GHz and a nominal gain of 22 dB. In addition, a Mini-Circuits SXHP-2+ high-pass filter, with a specified passband from 2 to 400 MHz, was inserted just before the Zeenko amplifier. These changes affect the loop magnitude and phase responses and may consequently alter which modes satisfy the oscillation conditions. The amplifier and filter specifications are provided in [11] and [12], respectively.

To acquire the spectrum shown in Figure 3, the analyzer was configured with a start frequency of 7.733412 MHz, a stop frequency of 42.597158 MHz, a span of 34.863746 MHz, an

RBW of 100 kHz, a VBW of 30 kHz, a reference level of -18.4 dBm, and an input attenuation of 5 dB. The effective loop gain was not measured directly at this stage; therefore, sustained oscillation was experimentally verified by the presence of stable spectral modes distinguishable from the noise floor.

III. PHYSICAL MODEL

This work considers an OEO based on direct modulation of the optical source. During each complete round trip, the signal propagates partly in the electrical domain and partly in the optical domain, with electro-optic (E/O) conversion in the LED and optoelectronic (O/E) conversion in the photodetector.

The Barkhausen phase condition can be formulated in terms of the effective delay of one complete round trip. In the model used here, the total loop delay, τ_{OEO} , is expressed as the sum of a length-independent effective delay, $\tau_0(f)$, associated with the optoelectronic devices, RF components, and electrical cables, and the average optical propagation delay $(n_{eff}/c)L$ along the POF. Therefore, the total round-trip delay can be written as in Eq. (1).

$$\tau_{OEO}(f, L) = \tau_0(f) + \frac{n_{eff}}{c}L \quad (1)$$

Considering the OEO FSR, its relationship with the total delay is given by Eq. (2).

$$\tau_{OEO} = \frac{1}{FSR_{OEO}} \quad (2)$$

In a reasonable realistic model, $\tau_0(f)$ is the frequency-dependent effective delay that includes the phase responses of the electrical and optoelectronic components. A significant contribution to $\tau_0(f)$ is associated with the LED, whose modulation bandwidth is approximately 14 MHz. Because the photodetector bandwidth is 150 MHz, its contribution is, to first order, smaller than that introduced by the LED. The amplifier contribution also tends to be smaller in the region where its response is approximately flat, but it may become relevant near or below its specified lower cutoff frequency.

IV. RESULTS AND DISCUSSION

When a POF segment of length L' instead of L ($L' \neq L$) is inserted into the OEO loop, the oscillation frequencies change because both the total phase and the loop power balance are both modified.

Because propagation in the SI-POF is strongly multimode, its description by a simple analytical model is limited. Temporal broadening due to multimode propagation and the optical launch conditions play important roles. In addition, $\tau_0(f)$ varies with oscillation frequency. For these reasons, calibration measurements, rather than direct use of (1) and (2), were adopted to model the relationship between L and FSR.

Figure 3 shows a typical RF spectrum measured at the OEO output for a POF of physical length $L = 26.3$ m. The spectrum shows the oscillation modes produced by the loop feedback condition. The FSR was determined from the difference between the center frequencies of two adjacent modes indicated in the Fig. 3. For this measurement, the modes were observed at $f_1 = 8.050$ MHz and $f_2 = 12.107$ MHz, yielding $FSR = f_2 - f_1 = 4.057$ MHz. This procedure was used to determine the FSR corresponding to the other POF samples of different L used for calibration.

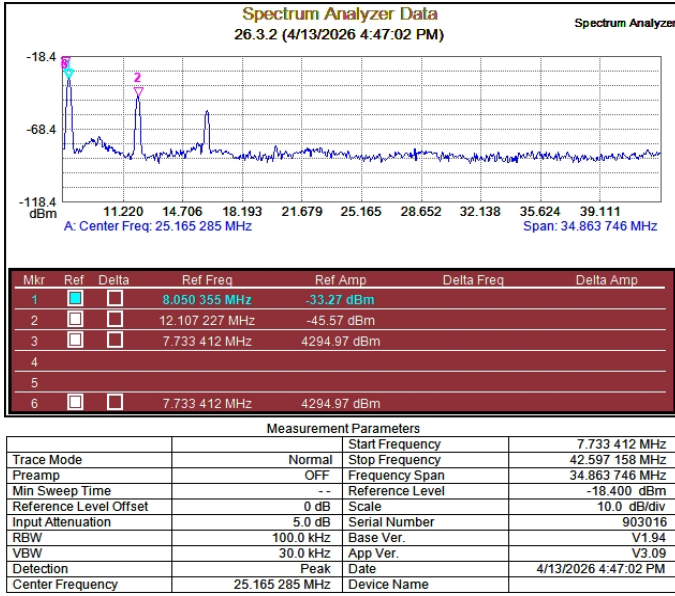


Fig. 3. OEO RF spectrum for a 26.3-m SI-POF, with an FSR of approximately 4.057 MHz between the indicated adjacent modes.

Figure 4 compares the calibration curves obtained for the original and modified OEO configurations. In both cases, the physical lengths of the samples were measured with a ruler, and the corresponding FSR values were determined using the electrical spectrum analyzer. The modified configuration included a reduction in the electrical-cable length, replacement of the amplifier, and insertion of a high-pass filter just before the new amplification stage.

The experimental values used for the two calibration curves are listed in Table I. For each calibration sample, the physical POF length was measured directly with a ruler, whereas the FSR was determined using the electrical spectrum analyzer from the difference between the center frequencies of two adjacent oscillation modes. The 14.67-m “unknown” POF was neither included in Table I nor used to obtain the fits.

TABLE I. POF SAMPLE LENGTHS AND MEASURED FSR VALUES.

POF length (m)	Original FSR (MHz)	Modified FSR (MHz)
0.15	18.003	—
0.485	17.368	—
2.24	13.241	18.0
5.00	9.952	12.0
9.30	7.226	9.6
17.10	5.325	6.8
22.00	4.374	—
26.30	4.057	5.2
31.40	—	4.4
46.07	—	4.0

In both configurations, the FSR decreases progressively as the POF length increases, which is consistent with the increase in the total OEO loop delay τ_{OEO} . Comparison of the two datasets makes it possible to evaluate the effect of the loop modifications on the relationship between POF length and FSR.

Because repeated FSR measurements were not performed for all samples, the repeatability and uncertainty of the method were not fully characterized at this stage. Therefore, the RMSE should be interpreted as a measure of the overall deviation of the fit from the calibration data, rather than as the uncertainty of the technique. The relative error of approximately 1% refers exclusively to the estimate for the 14.67-m “unknown” POF, which was not included in the calibration.

As an initial approach, the data from the original configuration, excluding the “unknown” POF, were fitted with a third-order polynomial obtained by linear least squares, yielding a root-mean-square error (RMSE) of approximately 0.683 m.

For the original configuration, Figure 4 also shows a hyperbolic fit obtained by nonlinear least squares according to the expected form $a/(x-b)$, with $a \neq 0$. This fit is given by Eq.(3).

$$L(\text{FSR}) = [87.9422/(\text{FSR} - 1.2163)] - 5.0544 \quad (3)$$

The hyperbolic fit for the original configuration yielded a root-mean-square error (RMSE) of approximately 0.403 m, corresponding to a typical calibration deviation of approximately ± 40.3 cm, lower than that obtained with the cubic-polynomial fit. To facilitate interpretation in monochrome printing, the experimental data and fits are distinguished by different markers and line styles in addition to color. When τ_0 is approximated as constant, (1) and (2) predict an inverse dependence between L and FSR, consistent with the hyperbolic form used. The lower RMSE of the hyperbolic model (0.403 m), compared with the cubic fit (0.683 m), provides qualitative experimental support for this trend. However, the residual differences and the inferred variation in $\tau_0(f)$ show that the simplified model does not quantitatively reproduce all the effects of multimode propagation and the component phase responses.

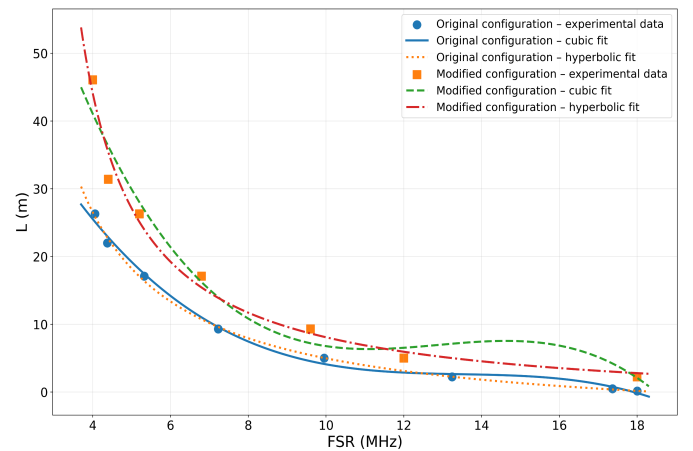


Fig. 4. Relationship between POF length and FSR for the original and modified configurations, with the corresponding cubic and hyperbolic fits.

For the modified configuration, the hyperbolic fit was described by $L(\text{FSR}) = 80.4557/(\text{FSR} - 2.2666) - 2.3207$, with an RMSE of approximately 1.915 m. The corresponding cubic fit yielded an RMSE of approximately 2.909 m. As in the

original configuration, the lower RMSE of the hyperbolic fit indicates better agreement with the expected inverse dependence.

The difference between the two curves shows that the relationship between POF length and FSR does not depend exclusively on the optical propagation delay. Shortening the cables modifies the electrical loop delay, whereas the new amplifier and the inclusion of high-pass filter alter the magnitude and phase responses of the feedback path. Although modal spacing is primarily associated with the total effective delay, the modes actually observed must also satisfy the Barkhausen magnitude condition. Thus, the new frequency response may favor or suppress particular modes and, together with the phase change, shift the oscillation frequencies and experimental FSR values. For the lengths common to both datasets, the modified configuration consistently yielded higher FSR values, which is consistent with a reduction in the total effective loop delay. In addition, this configuration extended the experimental range up to 46.07 m.

In the original configuration, the last two experimental points, corresponding to $L = 22.0$ and 26.3 m, were obtained by joining two POF segments with a single direct-contact splice between their end faces. Despite the additional attenuation introduced by the connection, the corresponding FSR values could still be measured.

For the “unknown” POF, an FSR of 5.641 MHz was measured in the original configuration. Because this sample was not used for calibration, the hyperbolic fit provided an independent estimate of $L = 14.82$ m. Subsequent measurement with a ruler yielded 14.67 m, corresponding to an absolute error of approximately 15 cm and a relative error of approximately 1.0%. In the original configuration, which used the 20 dB gain amplifier, no reliable results were obtained for lengths of 30 m or greater. By increasing the POF length also increases the optical attenuation, thereby reducing the signal amplitude at the photodetector output. When the amplifier gain no longer compensates for the optical and electrical losses, the Barkhausen magnitude condition is not satisfied, and the peaks become indistinguishable from the noise, preventing FSR measurement.

Assuming $n_{\text{eff}} = 1.48$ as the effective index of the PMMA SI-POF [13], the endpoints of the curve correspond to effective delays $\tau_0(f) \approx 54.8$ ns for $L = 0.15$ m and $\tau_0(f) \approx 116.7$ ns for $L = 26.3$ m. These values do not represent a constant physical delay, but rather the effective delay inferred after subtracting the estimated optical delay of the POF. The observed variation reinforces that $\tau_0(f)$, which is primarily associated with the LED dynamics and the phase responses of the other components, must vary with frequency.

V. CONCLUSIONS

This work described an unconventional OEO based on the combination of an LED and SI-POFs. The system enables the physical length of a sample to be estimated indirectly from the FSR. Once the $L \times \text{FSR}$ calibration curve has been established, the length L of a POF can be estimated. For the “unknown” POF, which was not included in the calibration dataset, the hyperbolic curve of the original configuration yielded an estimate of 14.82 m. Subsequent measurement with a ruler yielded 14.67 m, corresponding to a relative error of approximately 1.0%.

A more comprehensive evaluation requires additional samples that are not included in the calibration-curve fit,

preferably distributed across different regions of the length range. The technique may be particularly useful when both fiber ends are accessible but the complete route cannot be inspected or measured directly, as in fibers installed in ducts, panels, or structures.

In conventional OEOs with long singlemode fibers and high-speed components, the FSR is governed mainly by the fiber propagation delay. In the configurations analyzed here, however, the delays introduced by the cables, by the RF and optoelectronic components cannot be neglected. At higher frequencies, the limited LED bandwidth produces a larger phase shift, interpreted as an effective frequency-dependent optoelectronic contribution. In the original configuration, the experimental limitation close to 30 m resulted from the loop gain balance rather than from a fundamental limit of the method. Comparison of the curves showed that the modified configuration produced higher FSR values for similar lengths and extended the measurement range up to 46.07 m. This result reinforces that the calibration curve depends on the complete OEO configuration and must be reevaluated whenever relevant changes are made to the loop.

Future investigation may seek to increase the loop gain using avalanche photodetectors, higher-gain amplifiers, other wavelengths and improved optical alignment. Double-step-index (DSI) and graded-index (GI) POFs will also be investigated. Assuming a 1-kHz analyzer resolution, extrapolation of the hyperbola suggests that length differences could, in principle, be discriminated up to approximately 290 m.

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