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Implementation of Photonic True Time Delay Using High-Order-Mode Dispersion Compensating Fibers

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Abstract—We demonstrate the advantageous use of highly dispersive (>450 ps/nm km), high-order-mode (HOM) fiber modules for true time delay applications. Along with their low insertion loss, very low phase ripple (root mean square < 0.3° over 0–20 GHz), and high immunity to nonlinear effects, the high dispersion values facilitate the construction of devices with relatively short fibers, resulting in improved tolerance of the radio frequency delay to thermal changes. The implications of multiple path interference effects in HOM modules are also studied and shown to be very small.

Index Terms—Delay effects, microwave communication, multipath channels, optical fiber dispersion, optical modulation.

I. INTRODUCTION

M
ODERN radio frequency (RF) imaging systems are required to exhibit improved resolution, wider angular scans, and bandwidths exceeding 10% of the RF carrier frequency. These requirements have led to the development of photonic true time delay (TTD) technology for beam steering–forming in phased array radars, as well as in other applications [1]. Soref [2] has suggested the use of chromatic dispersion in optical fibers to produce wavelength-dependent delay through \( \Delta \tau = DL \Delta \lambda \), where \( \Delta \tau \) is the relative delay between two wavelengths, separated by \( \Delta \lambda \). \( D \) is the fiber dispersion coefficient (typically expressed in picoseconds/nanometers × kilometers), and \( L \) is the fiber length. While successfully demonstrated [3], the method suffers from two main shortcomings: signal walkoff and temperature drift. For double sideband modulation, signal walkoff is due to the difference in speed between the two modulation sidebands of the optical carrier, resulting in the cancellation of modulation for high enough RF frequencies [4], thereby limiting the useful RF bandwidth to values smaller than \( \sqrt{c/(2DL^2)} \), where \( c \) is the speed of light and \( \lambda \) is the optical wavelength of the carrier. More of a problem is the temperature drift of the RF phase, which is a direct consequence of the temperature dependence of the optical length of the fiber \( d(nL)/dT \) (\( n \) is the effective refractive index of the propagating mode). Since this thermal sensitivity is proportional to \( L \) while \( d\tau/d\lambda \) equals the product of \( D \) and \( L \), maximizing the fiber dispersion \( D \) will minimize the fiber length \( L \) and its associated \( d(nL)/dT \).

Highly dispersive high-order-mode (HOM) fibers have been recently introduced in the form of dispersion compensating modules (HOM-DCMs), [5], [6]. They comprise a length

![Experimental setup for the RF characterization of the HOM-DCM as a TTD device.](image)

of highly dispersive HOM fiber and two single-mode fiber pigtailed mode transformers (see the box in Fig. 1). Since HOM fibers exhibit dispersion coefficients much higher than those of regular dispersion compensating fibers (DCFs), [5], [6], HOM-DCMs should be able to implement TTD with significantly better tolerance of the RF delay to temperature variations. Moreover, due to their relatively large effective area, HOM-DCMs offer much higher tolerance to nonlinear optical interactions [7].

In this letter, we present for the first time the use of an HOM-DCM to implement TTD, with very low amplitude and phase ripples and improved thermal stability. While having many advantages, HOM-DCMs may also be afflicted by multiple path interference (MPI) [7], which could affect the delay characteristics of the device. This work also demonstrates that the currently achievable low MPI levels are sufficient for the proper operation of the HOM-DCM as a TTD.

II. EXPERIMENT

The experimental setup is depicted in Fig. 1. The RF signal from Port I of the 20-GHz vector network analyzer is used to intensity modulate the light from a tunable laser using an integrated-optics modulator. The light passing through the HOM-DCM is detected by an optical-to-electrical (O/E) converter and fed back to the analyzer, which measures the RF amplitude and phase as a function of the RF frequency for a given wavelength. The HOM-DCM under test comprised 105 m of HOM fiber, having \( D = 450 \) ps/(nm km) and a total dispersion of 47 ps/nm at 1550 nm, a fairly flat optical insertion loss of 3–3.5 dB over 50 nm (see top graph in Fig. 2) and an effective area of ~60 \( \mu \text{m}^2 \). Polarization-mode dispersion and polarization-dependent loss were smaller than 0.5 ps and 0.2 dB, respectively. A 20-GHz RF sweep was repeated for 26 equally spaced wavelengths and the phase and magnitude of the RF transfer function were recorded after per-wavelength calibration had been performed through a 4-m fiber patch cord.

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III. RESULTS

The resulting RF phase data $\phi_{\text{RF}}(f) - \phi_{\text{1557}}(f)$ (Fig. 3) follow straight lines, with less than 0.3° [root mean square (rms)] of fluctuations (top of Fig. 3). The sinusoidal nature of the phase fluctuations is indicative of MPI effects, as discussed below (Section IV). The wavelength dependence of the device delay and dispersion, $\tau(\lambda)$ and $D(\lambda)$, respectively, deduced from $\tau(\lambda) = -1/(2\pi) \cdot \partial \phi_{\text{RF}}(f)/\partial f$ and $D(\lambda) = \partial \tau(\lambda)/\partial \lambda$, appear in Fig. 2. The depicted accumulated dispersion in picoseconds/nanometers indicates dispersion values in excess of 450 ps/(nm · km) at 1550 nm, much higher than the ~90-ps/(nm · km) value, typical of regular DCFs. Also shown is the relatively flat optical insertion loss of the device in the range 1525-1575 nm. Fig. 4 displays the magnitude of the device RF transfer function for a few wavelengths. The electrical loss values at low RF frequencies are simply twice the optical insertion loss at the respective wavelengths, as deduced from the top frame of Fig. 2. Signal walkoff is responsible for the observed dispersion-dependent high-frequency rolloff, which is quite well characterized (dashed lines) by the small modulation index approximation $\cos^2(\pi \lambda^2 D L f^2/c)$ of [6] using the appropriate dispersion values from Fig. 2. Reference [8] assumes an optical medium with constant dispersion while for the HOM-DCM, $D(\lambda)$ versus $\lambda$ (or equivalently, $D(\omega)$ versus $\omega$, $\omega$ is the optical frequency in radians per second) exhibits wavelength dependence in the form of dispersion slope and some curvature. To study the effect of nonconstant dispersion, we followed common practice [8] and expanded $D(\omega)$ in a Taylor series around the frequency of interest, e.g., that of $\lambda_0 = 1550$ nm. Using recent formulations, which can deal with dispersion of any order [9], one finds that for the RF frequencies of our experiments, the correction due to high-order terms is negligible as is evident from the very good agreement of the measured data with the results of the constant dispersion theory [8].

The temperature sensitivity of the delay of a fiber-based TTD is proportional to the fiber length, and is mainly determined by the temperature sensitivity of the fiber effective refractive index. Normalizing $d\tau/dT$ by the device length, we experimentally found the HOM-DCM at 1550 nm to be characterized by $L^{-1}d\tau/dT = 55$ ps/(°C · km). For comparison, a 300-ps/nm 3500-m-long commercial DCF ($D = 86$ ps/(nm · km)], was found to have $L^{-1}d\tau/dT = 36$ ps/(°C · km). But for the same TTD performance, as measured by $d\tau/d\lambda$, the HOM-DCM is five times shorter than a regular DCF, resulting in a temperature dependent delay $d\tau/dT$ one third its DCF counterpart. While modest, this improvement may prove useful in some applications and certainly eases the requirements when active temperature stabilization of the HOM-DCM is employed.

IV. EFFECT OF MPI IN HOM-DCMs

A small portion of the light entering the HOM-DCM can reach the output fiber through paths other than the desirable LP12 mode, resulting in MPI in the O/E converter [7]. In order to get an estimate of the impact of MPI on the phase of the RF transfer function, we will assume a single parasitic path, so that the HOM-DCM can be modeled as a Mach–Zehnder interferometer. In the model, the asynchronously copolarized parasitic signal has a differential delay of $\Delta \tau$ with respect to the main path, and its additive contribution to the output signal is attenuated by an amplitude factor $\sqrt{\varepsilon}$ ($\varepsilon$, a small number, quantifies the level of MPI in the device). The optical transfer function of such a device is proportional to $1 + \sqrt{\varepsilon} \cdot \exp[i\omega \Delta \tau]$. We assume an intensity modulated input optical field of the form $E_{\text{in}}(t) = \sqrt{I} [1 + 0.5m \cdot \cos(2\pi ft + \phi_{\text{RF}})] \cdot \exp[i\omega t]$, where
\( I \) is the average intensity, \( m \) is the (small) modulation index, and \( \omega_0 \), \( f \), and \( \phi_{RF} \) are the optical frequency, RF frequency, and phase variations, respectively. Applying the above-mentioned device transfer function to the input optical signal, calculating the resulting output intensity and retaining only terms at the RF frequency \( f \), we get

\[
I_{\text{RF}}(t) \propto [1 + \delta I_{\text{MPI}}] \cdot \cos(2\pi ft + \phi_{RF} + \delta \phi_{\text{MPI}}) \tag{1}
\]

where \( \delta I_{\text{MPI}} \) and \( \delta \phi_{\text{MPI}} \) represent MPI-induced RF amplitude and phase variations, respectively, and for \( \varepsilon \ll 1 \), they are given by

\[
\delta I_{\text{MPI}} = \sqrt{\varepsilon} \cdot \cos(\omega_0 \Delta \tau) \cdot [1 + \cos(2\pi f \Delta \tau)]
\]

\[
\delta \phi_{\text{MPI}} = \sqrt{\varepsilon} \cdot \cos(\omega_0 \Delta \tau) \cdot \sin(2\pi f \Delta \tau). \tag{2}
\]

For a fixed \( \Delta \tau \) (practically of the order of nanoseconds to tens of nanoseconds), both \( \delta I_{\text{MPI}} \) and \( \delta \phi_{\text{MPI}} \) are periodic functions of \( f \), with amplitudes which depend on \( \sqrt{\varepsilon} \), as well as on \( \cos(\omega_0 \Delta \tau) \). Since \( \omega_0 \approx 10^{15} \text{ rad/s} \), \( \cos(\omega_0 \Delta \tau) \) is very sensitive to minute environmentally induced variations of \( \Delta \tau \) (and/or \( \omega_0 \)), resulting in constant drifting of \( \delta I_{\text{MPI}} \) and \( \delta \phi_{\text{MPI}} \). State-of-the-art HOM-DCMs, including the tested unit, exhibit MPI values below \(-45 \text{ dB} \) \((\varepsilon < 3 \cdot 10^{-5})\) across tens of nanometers around 1550 nm [7], resulting in extremely low MPI-induced phase and amplitude ripples of \(<0.3^\circ\) and \(<0.05 \text{ dB} \), respectively. In a real HOM-DCM, there are quite a few different contributions to MPI, having different differential delays, and \( \delta I_{\text{MPI}} \) and \( \delta \phi_{\text{MPI}} \) will generally exhibit more random dependence on \( f \), but their variances will still be on the order of \( \varepsilon \) (as shown). To validate this analysis, a Mach–Zehnder interferometer was constructed, with an attenuator in one arm to simulate a given value of MPI. The test setup was identical to the one used for characterizing the HOM-DCM (Fig. 1) except for the change in the device under test. The time delay between the two arms of the interferometer was set to \( \sim 2 \text{ ns} \), while the coherence time of the tunable laser exceeded 10 \( \mu \text{s} \). In addition, a polarization controller was used to ensure maximum interference at the detector. The modulation frequency \( f \) was scanned over a few gigahertz, to allow for several full periods of the sine function to be observed, and the amplitude of the sinusoidal variations of \( \delta \phi_{\text{MPI}} \) as a function of \( f \) (2) was measured for different MPI values. Fig. 5 shows the dependence of the measured amplitude of \( \delta \phi_{\text{MPI}} \) on the level of MPI, which according to (2) should fit a straight line with a unity slope.

Based on this treatment, the measured RF phase fluctuations (top frame in Fig. 3) can indeed be interpreted as a manifestation of the device MPI. The period of the sinusoidal ripple (\( \sim 0.6 \text{ GHz} \)) indicates (see (2)) a delay difference of \( \Delta \tau = 1.6 \text{ ns} \), which is commensurate with the calculated difference in group velocities between the LP01 and LP02 modes. To check with the model, the amplitude of the fluctuations was experimentally found to depend on the input polarization (Fig. 3 shows its maximum) and its value of \( \sim 0.4^\circ \) is quite well predicted by (2) for an MPI of 10 log_{10}, as measured by the wavelength scanning method.

V. Conclusion

We have demonstrated that HOM fibers, having dispersion coefficients much higher than those of DCFs, can implement photonic TTD, using shorter fibers, resulting in lower temperature dependence of the total delay. Through proper design, even higher dispersion values can be achieved. Very good RF performance (amplitude and phase ripples of less than 0.05 dB and 0.3° rms, respectively) was experimentally demonstrated over 20 GHz of bandwidth. The issue of MPI in HOM-DCMs was addressed both analytically and experimentally, resulting in an estimate that currently available MPI values should be low enough for most TTD RF applications. Further improvement of both the thermal and signal walkoff performance can be achieved by decreasing the value of \( D \cdot f \), at the expense of employing widely tunable lasers (>100 nm of continuous tuning).

REFERENCES