Photonic crystal fibers for microwave signal processing

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***Abstract*— We present a novel design of an optical True Time Delay Line based on a 19-core Photonic Crystal Fiber that operates in a broad radiofrequency signal processing range from 1 to 67 GHz on a 10-km link, thus enabling simultaneous microwave signal distribution and processing.**

***Keywords*— Microwave photonics, multicore fibers, photonic crystal fibers, spatial division multiplexing.**

I. Introduction

Space-division multiplexing fibers offer the potential to provide distributed microwave signal processing in fiber-wireless communications scenarios with advantages in terms of increased compactness along with performance flexibility and versatility, [1,3]. In this work, we propose pure silica multicore Photonic Crystal Fibers (PCFs) as True Time Delay Lines (TTDLs) for radiofrequency (RF) signal processing. TTDLs are actually the basis of most microwave signal processing applications, such as radio beam-steering for phased array antennas, optoelectronic oscillation or signal filtering [4]. To operate as a sampled tunable TTDL, each fiber core must feature a different value of both the group delay and the chromatic dispersion in a specific incremental trend. Since PCFs offer more control over chromatic dispersion than solid fibers, we have been able to design a 19-core PCF that extends the dispersion range from 0 up to 35 ps/nm/km with a smaller value of dispersion slope, S (maximum 0.031 ps/nm^2/km); thereby, increasing the previously reported number of samples in solid multicore fibers [1] from 7 to 19. When we operate the TTDL exploiting the fiber spatial diversity (samples provided by cores), we get a tunable basic differential delay between samples $\Delta\tau$ that depends on the incremental chromatic dispersion between cores, ΔD. This translates into a theoretical RF signal processing range (given by the inverse of $\Delta\tau$) from 24 up to 1210 GHz.km in a wavelength window of ±50 nm around the central wavelength, broader than that for a solid multicore fiber [1] (33.35 up to 1000 GHz.km in a ±30 nm wavelength window). If we operate the TTDL by using wavelength diversity (samples provided by different optical wavelengths), each core individually offers TTDL functionality as well, where $\Delta\tau$ depends on the wavelength spacing, $\Delta\lambda = \lambda_{m+1}-\lambda_m$. The RF signal processing range in this regime is only 49 to 70 GHz.km for the solid 7-core MCF [1], whereas, using PCFs we can extend it from 64 to 1333.3 GHz.km. Another major advantage of PCF technology is the higher index contrast between air and silica that enables low confinement loss, greater immunity to bends as well as low intercore crosstalk. Moreover, silica glass is cheaper than doped glass.

II. Design of a Multicore PCF as TTDL

The design consists of a heterogeneous multicore PCF where each of its 19 silica cores features an independent group delay and chromatic dispersion, thus enabling operation as a tunable TTDL. Fig. 1(a) illustrates the basic principle of a tunable sampled TTDL built upon a multicore PCF operating in space diversity. At the input, the RF modulated signal is evenly split across the N cores of the fiber. To function as a TTDL, each core must have an independent group delay, τ, which increments linearly for successive cores by $\Delta\tau$. Thus, we get a set of N time-delayed signal samples of the RF signal at the fiber output. In addition, delay tunability with the optical wavelength requires linearly increasing values of the chromatic dispersion D between cores (i.e., keeping a constant incremental dispersion, ΔD, between consecutive cores) and a minimum contribution of higher-order dispersion effects.

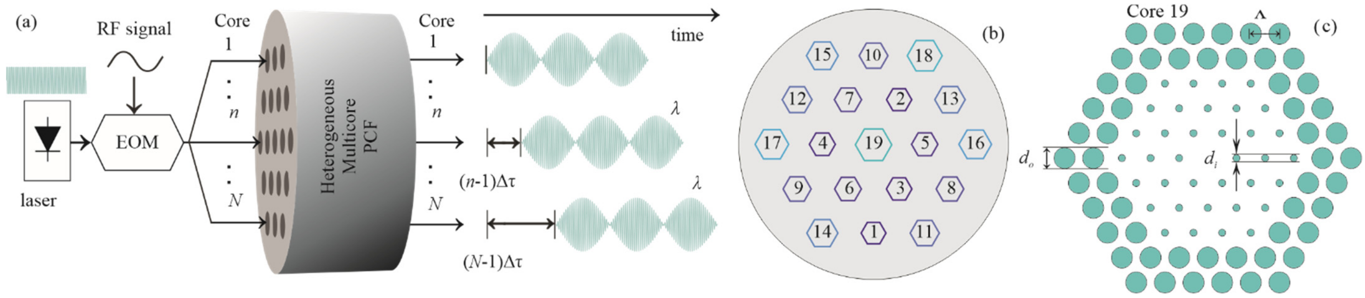

Fig. 1. Schematic of (a) a sampled TTDL based on a heterogeneous multicore PCF exploiting the fiber spatial diversity; (b) cross-section of a heterogeneous 19-core PCF, individual cores represented by numbered hexagons with Λ_{core} = 36 μm; (c) core 19 in close-up for which d_i = 0.87 μm, d_o = 2.42 μm and Λ = 3.08 μm.

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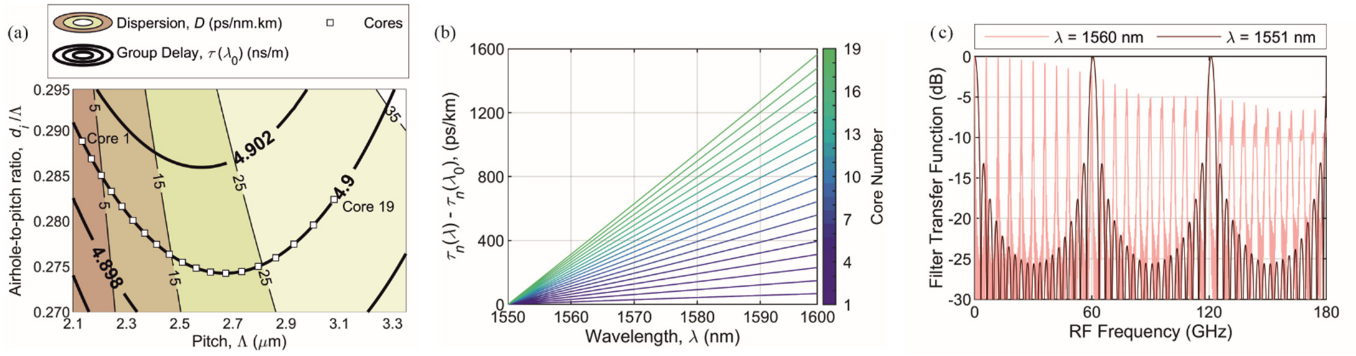

Fig. 2. (a) Contour plot for chromatic dispersion (thin lines) and group delay (thick lines) as a function of Λ and d_i/Λ at λ_0. Cores 1 to 19 are marked by white squares. (b) Group Delay difference, $\tau_n(\lambda) - \tau_n(\lambda_0)$ in ps/km for all cores (right axis) as a function of the optical wavelength. (c) Transfer function of a microwave signal filter based on the proposed TTDL for a 10-km link operating in the spatial diversity regime.

For core n, τ is expanded as $\tau_n(\lambda_0) + D_n(\lambda-\lambda_0) + S_n(\lambda-\lambda_0)^2/2$, where D_n and S_n represent, respectively, chromatic dispersion and dispersion slope at the anchor wavelength, λ_0. In space diversity, $\Delta\tau = \Delta\tau_{n+1} - \Delta\tau_n$ depends mainly on ΔD, i.e. $\Delta\tau = \Delta D\,(\lambda-\lambda_0) + \Delta S\,(\lambda-\lambda_0)^2/2$; while for wavelength diversity, it depends on the separation between adjacent wavelengths $\Delta\lambda$, since $\Delta\tau = D_n + S_n\Delta\lambda^2/2$.

Fig. 1(b) shows the proposed layout for the arrangement of 19 PCF cores with an intercore spacing Λ_{core} of 36 μm and a cladding diameter of around 250 μm. Each hexagon represents a pure fused silica glass PCF, with 5 rings of airholes, shown up-close in Fig. 1(c). This basic structure is based on a zero- and flat-dispersion PCF design [2] featuring two different airhole sizes, d_i (those in the three inner rings) and d_o (those in the two outer rings), while inter-airhole pitch or spacing, Λ, is constant. To get 19 different cores from this basic structure, we vary Λ and d/Λ while keeping $d_i = 0.36\, d_o$.

The propagation analysis carried out at the anchor wavelength λ_0 = 1550 nm is captured in Fig. 2(a), where white squares mark the selected 19 cores. The overall D covers a range from 1.5 up to 31.2 ps/nm.km, keeping a constant incremental dispersion ΔD = 1.65 ps/nm/km. Moreover, d/λ is chosen such that every core lies on a contour line (thick line) corresponding to $\tau(\lambda_0)$ = 4.9 ns/m.

III. TTDL Performance Evaluation

Fig. 2(b) shows the group delay difference, $\tau_n(\lambda) - \tau_n(\lambda_0)$, as a function of the operation wavelength for the proposed design. We achieve an ideal TTDL functionality by fulfilling two conditions: First, we get zero $\Delta\tau$ at the anchor wavelength λ_0. Secondly, $\Delta\tau$ increases linearly between cores because the dispersion increases in fixed increments of ΔD.

Satisfactory performance as a tunable TTDL requires the relative error due to higher-order dispersion in both space and wavelength diversities to remain below 10% [3]. In our design, the relative error in space-diversity regime ((3) in [3]) increases up to 6% at an offset of ±50 nm from 1550 nm. Whereas, the relative error in the wavelength diversity regime ((5) in [3]) is less than 7% for all cores, assuming the first optical wavelength λ_1 is 1580 nm and $\Delta\lambda$ is 1 nm.

To study the performance of the designed TTDL as a signal processing element, we evaluated an RF signal filter. Fig. 2(c) shows the 19-tap filter emulated for our design when operating in the spatial diversity regime for a 10-km link. The Free Spectral Range (FSR) of the filter, computed as FSR = $1/\Delta\tau$ [4], goes from 6 to 60.6 GHz respectively for optical wavelengths of 1551 and 1560 nm.

IV. Conclusions

We have proposed the use of multicore PCFs to implement a broadly tunable TTDL for microwave signal processing. A 19-core PCF is designed and evaluated as a TTDL and applied to a representative microwave photonics application of an RF filter. Beyond this, the applicability of the proposed TTDL extends to additional microwave signal processing functionalities, such as arbitrary waveform generation, optical beamforming for phased-array antennas or multicavity-optoelectronic oscillation. The potential fabrication complexity for the proposed design is balanced by a considerable number of TTDL samples, i.e., 19, broad RF signal processing range (1 to 67 GHz for 10 km), high index contrast (up to 1.52%), low confinement losses (as low as 10^{-5} dB/km) and lower fabrication cost as compared with state-of-the-art SDM-based TTDLs.

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