Distributed-Phase OCDMA Encoder–Decoders
Based on Fiber Bragg Gratings
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Abstract—We propose and demonstrate new optical code-division multiple-access (OCDMA) encoder–decoders having a continuous phase-distribution. With the same spatial refractive index distribution as the reconfigurable optical phase encoder–decoders, they are inherently suitable for the application in reconfigurable OCDMA systems. Furthermore, compared with conventional discrete-phase devices, they also have additional advantages of being more tolerant to input pulselength and, therefore, have the potential of bandwidth saving.

Index Terms—Code-division multiplexing, fiber-optics communication, gratings, optical fiber devices.

I. INTRODUCTION

Optical code-division multiple-access (OCDMA) systems based on superstructured fiber Bragg gratings (SSFBGs) have been demonstrated as a promising technique for future optical networks [1]–[3]. SSFBG encoder–decoders, with a spatial phase distribution following a particular address code, can be easily designed and fabricated to achieve temporal-phase-encoding, which provides far better correlation performances than the amplitude-only encoding [1]. In the encoding process, the optical pulses are reflected from SSFBG encoders, and the spatial phase of encoders is encrypted into the temporal phase of encoded pulse. For successful decoding, the encoded pulses must be reflected from an SSFBG decoder with a conjugate address code to the encoder. The conventional SSFBG encoder–decoders are discrete-phase encoder–decoders because spatial phase distributions in them are formed by inserting discrete phase-shifts.

To enhance the flexibility of this approach, we recently demonstrated a reconfigurable OCDMA phase encoder–decoder, which is composed of a uniform fiber Bragg grating (FBG) and a series of equidistant tungsten wires in contact with the FBG [4]. Electrical currents pass through the wires, heat the wires and FBG, and produce a background refractive index variation. This constitutes a phase shift in the FBG, which can be tuned by varying the electrical currents through tungsten wires. Because the thermally induced dc (background) refractive index distribution usually covers a length of several millimetres, phase shifts in a reconfigurable-phase encoder–decoder are inherently continuous. In previous demonstrations, a reconfigurable phase decoder was used to retrieve the signals from discrete-phase encoders. Therefore, the phase distribution of decoders can only approximately match that of encoders.

In this letter, we propose and experimentally demonstrate a novel fixed and continuous-phase encoder–decoder with a phase profile designed to match a reconfigurable en/decoder accurately. This new continuous-phase device has the inherent advantage to operate together with reconfigurable-phase devices in reconfigurable OCDMA systems.

II. DEVICE DESCRIPTION AND SIMULATION

Two 16-bit quaternary codes Q1 and Q2 are chosen from the family A sequences [5]. Q1C and Q2C denote the fixed-code continuous-phase-encoders, and Q1D and Q2D represent the fixed-code discrete-phase-encoders, while Q1R and Q2R represent the reconfigurable-phase-encoders. Q1C*, Q2C*, Q1D*, Q2D*, Q1R*, and Q2R* are corresponding decoders. Their chip lengths are all 2.5 mm.

For discrete-phase en/decoders, a spatial gap ΔL in the grating structure constitutes a phase-shift φ = (4π/λB)nδkΔL. While for continuous-phase en/decoders or reconfigurable-phase-en/decoders, phase-shifts are given by φ = (4π/λB)∫ δnδk(x)dx, where δnδk(x) is the additional dc (background) refractive index variation [4].

Q1R and Q2R are the reconfigurable en/decoders reported in [4]. Using the pulse response method [6], we characterize the distribution profile of thermally induced single phase-shift 0.5π, 1.0π, or 1.5π, and the measured results are approximated by hyperbolic secant square functions as shown in Fig. 1(a). Note that this result is slightly different and more accurate than that reported in [6] because we use a shorter (~5 ps) input pulse in

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this measurement. The dc refractive index distribution in $Q1R$ or $Q2R$ is obtained by adding the dc refractive index distribution corresponding to all the spatially displaced phase-shifts. The dc effective refractive index distribution of $Q1R$ is shown in Fig. 1(b). Note that the dc refractive index distribution of a reconfigurable-phase en/decoder can also be directly measured using the pulse response method [7].

The novel fixed-code continuous-phase-encoders $Q1C$ and $Q2C$ are, respectively, designed to have the same effective dc refractive index distributions as that of the reconfigurable encoder $Q1R$ and $Q2R$. Therefore, shown in Fig. 1(b) is also the dc effective refractive index distribution of $Q1C$.

The phase profile of discrete-phase-encoder $Q1D$ is shown in Fig. 1(c) for comparison. Note that $Q1D$, $Q1R$, and $Q1C$ have identical phase code sequences.

By simulation, we compare the performance of OCDMA systems with three different configurations: (a) discrete-phase encoders and decoders, (b) discrete-phase encoders and continuous-phase decoders, or (c) continuous-phase encoders and decoders. The input pulsewidth is 5 ps, and the peak reflectivity of all the FBGs for the simulation is $\sim$10%. The results are shown in Fig. 2 as the codes $Q1$ and $Q2$ are used. Based on comparing the ratio between the peak of cross and auto correlation (RPCA), we find that configuration (a) has the best performance, although only marginally when compared with (c). Simulations based on other code sequences show similar results. The better performance of configuration (c) over (b) is due to the fact that the encoder and decoder in (c) are both continuous and can, therefore, match completely. A special advantage of configuration (c) over (a) is that the continuous-phase devices can be achieved with the capacity of dynamic reconfiguration.

III. DEVICE FABRICATION AND CHARACTERIZATION

The FBG en/decoders are fabricated using our continuous grating writing technique [8], which uses a phase mask with uniform pitch and relies on precise control of the position of the fiber relative to phase mask to achieve gratings with complex profiles. The effective dc refractive index variation $\delta n_{dc}$ in the continuous-phase en/decoders ($Q1C$, $Q2C$, $Q1C^*$, and $Q2C^*$) is achieved by chirping the Bragg wavelength $\lambda_B$ (according to the equation $\delta n_{dc} = (\delta \lambda_B/\lambda_B)n_{dc}$). For comparison, we also fabricate discrete-phase en/decoders ($Q1D$, $Q2D$, $Q1D^*$, and $Q2D^*$) and reconfigurable en/decoders ($Q1R$, $Q2R$, $Q1R^*$, and $Q2R^*$). The Bragg wavelength, effective index modulation, chip length, and total length of all the gratings are, respectively, 1550.5 nm, 2.2 $\times 10^5$, 2.5 mm, and 40 mm. Peak reflectivity of all the FBGs for experiments is $\sim$40%. We choose a slightly higher index modulation to obtain a lower insertion loss from the en/decoding FBGs.

Fig. 3(a) and (b) shows the simulated (dashed lines) and measured (solid lines) reflection spectra of continuous-phase-encoders $Q1C$ and $Q2C$. There is clearly good agreement between the measurement and simulation results although the grating structures are very complex, as shown in Fig. 1(b). Shown in Fig. 3(c) and (d) are the simulated and measured reflection spectra of reconfigurable-phase-encoders $Q1R$ and $Q2R$. The measurement roughly agrees with the simulation result, which is based on the characterization results on the single phase distribution, as shown in Fig. 1(a). Note that the simulated spectra of continuous-phase-encoders and reconfigurable-phase-encoders are the same. Shown in Fig. 3(e) and (f) are the reflection spectra of discrete-phase-encoders $Q1D$ and $Q2D$. For the same nominal address codes, the reflection spectra of the continuous-phase-encoders (and also reconfigurable-phase-encoders) are narrower than those of the discrete-phase-encoders and they also have much lower spectral
features away from the main band, which could assist their use in a wavelength-division-multiplexing (WDM) configuration.

IV. DEVICE PERFORMANCE AND DISCUSSION

The codes are all tested using a gain-switched laser diode, operating at 1550.5 nm, and generating \( \sim 5 \)-ps pulse sequences with a repetition rate of 311 MHz. This pulse train is split by a 3-dB coupler into two parts, each reflected from the continuous-phase encoders \( Q1C \) and \( Q2C \), respectively, and then combined by another 3-dB coupler. A fiber delay line controls the timing of the signals from the two encoding gratings. Then the combined signal is reflected from the continuous-phase decoders \( Q1C^* \) or \( Q2C^* \). The decoded pulses are detected using a 20-GHz photodiode and fed into a fast sampling oscilloscope. The measured auto- and cross-correlation pulses, for the decoders \( Q1C^* \) or \( Q2C^* \), are shown in Fig. 3(a). The measured RPCA is \( \sim 20\% \).

Then, we measure the system using the continuous-phase encoders \( Q1C, Q2C \) and reconfigurable phase decoders \( (Q1R^* , Q2R^* ) \) [Fig. 4(b)]. The measured RPCA is \( \sim 23\% \). Note that in Section II, we have demonstrated that continuous-phase encoders can match better with reconfigurable decoders compared with the discrete-phase encoders by simulation.

We also measure the system using the discrete-phase encoders \( (Q1D , Q2D ) \) and decoders \( (Q1D^* , Q2D^* ) \) [Fig. 4(b)]. In this case, the measured RPCA is \( \sim 20\% \). For further comparison, the performances of systems using continuous-phase or discrete-phase devices with the same chip duration and code sequences are simulated under different input pulsewidths. The resultant RPCAs are summarized in Fig. 5 (peak reflectivity of all the FBGs for the simulation is \( \sim 10\% \)). We can see that the system using the continuous-phase en/decoders is more tolerant to longer input pulsewidths. This we believe can be explained by the fact that the reflection spectrum of the continuous-phase device is narrower than that of the discrete-phase device, as shown in Fig. 3.

V. CONCLUSION

We have demonstrated a novel OCDMA en/decoder with a continuous phase distribution based on FBGs. One advantage of the new code design is that it provides a better match to a reconfigurable en/decoder, because it has the same spatial phase distribution as a reconfigurable device. The performance of the continuous-phase devices is also compared with a system using the discrete-phase devices. Its advantage includes that it has a more relaxed requirement on the encoding input pulsewidth. This suggests the potential of bandwidth saving, and could facilitate the combination of an OCDMA system with existing WDM techniques to enhance system capacity further.

REFERENCES


Fig. 4. Measured decoded pulses for systems using (a) continuous-phase encoders and decoders, (b) continuous-phase encoders and continuous-phase decoders, and (c) discrete-phase encoders and decoders.

Fig. 5. Simulated RPCA for systems using continuous- or discrete-phase en/decoders for different input pulsewidths.