Reconfigurable Multiport Optical Encoder/Decoder With Enhanced Auto-Correlation

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***Abstract*—A novel planar configuration of a multiport encoder/decoder (E/D) is presented that has enhanced performance in terms of beat-noise suppression and network confidentiality. We insert a splitter and a set of phase shifters in front of a standard arrayed-waveguide-grating-based multiport E/D to generate spectral-phase codes. The new configuration keeps the same key features and it is able to generate/process a set of different codes simultaneously; at the same time, the network confidentiality is enhanced, because only the intended receiver, which knows the phase-shifter values, is able to recognize the code. Furthermore, whereas the auto-correlation function of the previous E/D has a triangular shape, in this case it is similar to the input pulse, enhancing the system cascadability and reducing the beat noise.**

***Index Terms*—Code-division multiple-access, code-division multiplexing, decoding, encoding, optical fiber communication, optical planar waveguide components.**

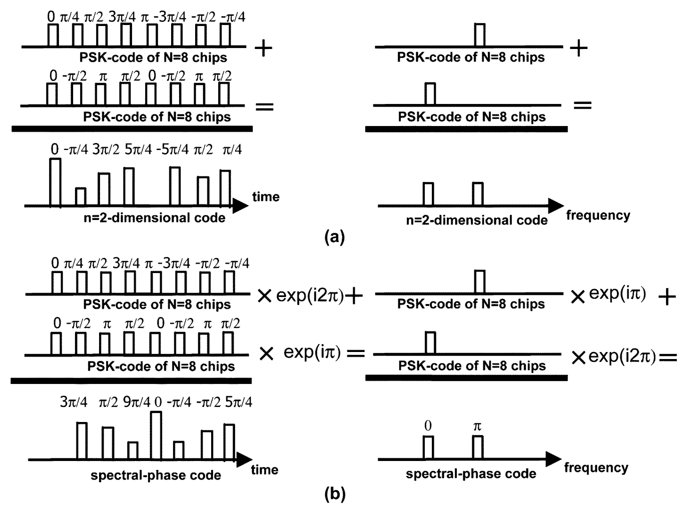

Fig. 1. Schematic of the code generation in time and frequency domains (a) multidimensional code ($n = 2$); (b) spectral-phase code.

I. INTRODUCTION

OPTICAL code-division multiplexing, optical packet switching (OPS), and optical burst switching (OBS) are currently among the most investigated research topics in optical communications, with their common feature to provide flexible broadband access to a large number of users in high-speed networks. These transmission systems rely on optical codes, or labels, that are used to route optical packets and bursts, or to access the shared medium in an asynchronous way. Many different direct-sequence spread-spectrum and spectral phase-encoded time-spreading techniques have been proposed in literature, where optical codes are generated either in time or frequency domains [1]–[5]. In the first case, the codes are constituted of copies of an input pulse, that are called time chips, with different phases and/or intensities. The time-spreading techniques are time-frequency reversed versions of direct-sequence methods, where the spectrum of an ultrashort pulse is split into many frequency channels, that are phase-encoded.

Recently, we designed an innovative planar multiport encoder/decoder (E/D) that is able to generate/process N phase-shifted-keying (PSK) codes simultaneously [6]. The device has an arrayed waveguide grating (AWG) configuration, and we input a short (about 2 ps) laser pulse into one of the encoder ports, to generate a set of optical codes, using a direct-sequence technique. The codes are processed using the same passive (reciprocal) device: when forwarding a code into one of the decoder input ports, at its outputs we measure the cross-correlation signals, and the auto-correlation peak (ACP) detected at one of the device outputs identifies the code. Since each code corresponds to a different frequency subchannel, that does not overlap the others, the cross-correlation between two codes is small. The code cardinality coincides with the number of the device ports, and to increase this parameter, we proposed a multidimensional configuration where two or more laser pulses are sent into different encoder input ports [7]. In this case, a set of $n \leq N$ laser pulses are sent simultaneously into n encoder input ports to generate a set of n-dimensional codes that are coherent sums of n PSK codes. The corresponding spectrum is composed of n nonoverlapping frequency subbands, as shown in Fig. 1(a).

In this letter, we introduce a novel configuration of the multiport E/D, where a set of phase shifters are inserted at its input ports. In this way, we can change the phases of the input coherent laser pulses in the multidimensional configuration, obtaining the spectral-phased E/D of Fig. 1(b). This configuration has three advantages, with respect to the previous one: larger code cardinality, reduced autocorrelation sidelobes, and enhanced security, since the encoding key is related to the phase-shift values. We also observe that the proposed encoding scheme can be considered as a spectral phase-encoded time-spreading technique

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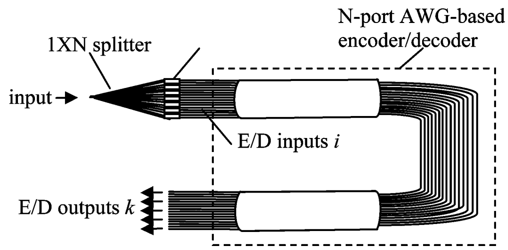

Fig. 2. Architecture of the spectral-phase E/D consisting of an AWG, an input splitter, and an array of phase shifters.

that was first proposed by Salehi *et al.* [4]; compared to other spectral schemes, the E/D proposed in this letter has the advantages of being implemented monolithically within a single planar device, and that multiple codes can be simultaneously generated/processed.

II. New Device Configuration

The new device architecture is shown in Fig. 2: the AWG-based E/D has N input/output ports and a free-spectral range (FSR) $1/\tau$, where τ is the delay between two adjacent array waveguides. The input pulse is split in as many copies as the number of the input ports of the multiport E/D and a set of multidimensional codes are generated at its output ports. Furthermore, the phase shifters change the phases of the input pulses to generate phase-shifted multidimensional codes. Our previous experience with a fabricated device demonstrates that the close proximity of the thermal phase shifters will not be problematic.

To better explain the functionality of the new optical device, we can consider the reciprocal configuration, exchanging input and output ports. If a single laser pulse is sent into the port k, N different codes are generated at the ports $i\,(i = 1, 2, \ldots N)$, that are phase shifted and summed together by the splitter to generate a spectral-phase code. Each code generated by the multiport E/D corresponds to a shifted version of a subband optical filter $H(f)$ that has an FSR equal to $1/\tau$; therefore, the transfer function from the input to the output $k(k = 1, 2, \ldots N)$ of the novel E/D configuration is

$$H_k(f) = \sum_{i=0}^{N-1} e^{-j\Phi_i} H\left(f - \frac{i+k+1}{N\tau}\right) \qquad (1)$$

where $\varPhi_i$ are the phase-shift values.

We generate a pseudorandom binary spectral-phase code, with phase shifts 0 or π applied to $N = 15$ coherent laser pulses, sent to the multiport E/D input ports. The spectral-phase code intensity and the corresponding frequency spectrum are reported in Fig. 3(a) and (b), respectively; the matched and unmatched decoded signals, are shown in Fig. 3(c) and (d). In this case, we assumed FSR $= 200$ GHz, and a pulse laser width (i.e., time chip duration) of $\tau = 2$ ps. The signals corresponding to a PSK code generated by the multiport E/D in a standard configuration (without splitter and phase shifters) are plotted in the same figure with a dotted line, for comparison. We observe that the time chips of a spectral-phase code have unequal intensities (and phases) because they are the sum of N PSK codes with random phases; the spectrum corresponding to a PSK is a single subband frequency channel with bandwidth FSR/N,

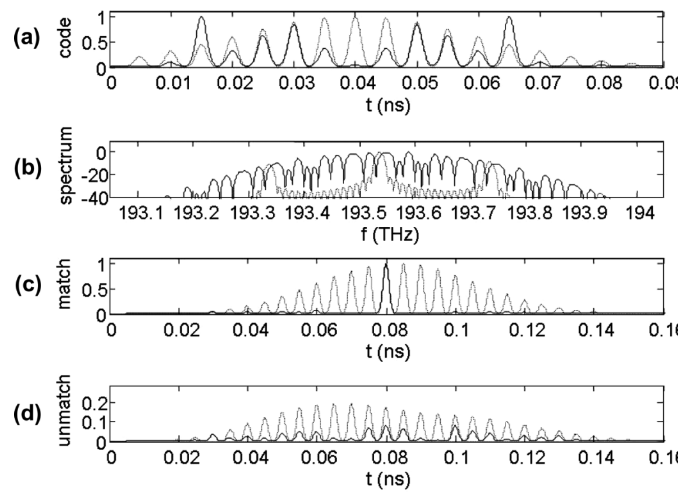

Fig. 3. (a) Intensity of the code; (b) spectral content; (c) auto-correlation; (d) cross-correlation. Continuous line refers to a spectral-phase code with random phase and dotted line to a PSK code.

whereas all the frequency channels (with random phases) are in the spectrum of the spectral-phase code [see Fig. 3(b)].

The main advantage of the new configuration is that the auto-correlation signal is identical to the input pulse, whereas the auto-correlation signal of PSK codes has a triangular envelope [see Fig. 3(c)]. This feature allows us to reduce the influence of beat noise [8] and also to enhance the cascadability of a set of E/Ds. The second fundamental advantage of the novel device is that the phase shifters introduce an additional degree of freedom for the code generation: for each set of phase-shift values, the advanced multiport E/D generates a different family of N codes; therefore, the system confidentiality is greatly enhanced because an eavesdropper who does not know the phase-shift values is not able to recognize the code.

The code detectability, i.e., the ratio between the auto- and cross-correlation peaks, depends on the phase-shift values; in the case of Fig. 3, it is about 6.9 dB for the spectral-phase codes, and 6.5 dB for the PSK codes.

III. Optimal Phase Values

To guarantee that the code detectability is the same for all the codes, an accurate choice of the phase-shift values is necessary. For the sake of clearness, in the following we will refer only to binary (0, π) phase values, but it is possible to extend the selection criteria to arbitrary values without any loss of generality, if the matched phases at the decoder are the conjugate of the corresponding values at the encoder.

The cross-correlation function between two codes generated at ports k and k' of the new multiport E/D can be evaluated both in time and frequency domains; in the latter case, it is

$$c_k(t) * c_{k'}(t) = \int H_k(f) \cdot H_{k'}(f) e^{-j2\pi f t} df \qquad (2)$$

and, substituting (1) into (2), we obtain

$$c_k(t) * c_{k'}(t) = \int \sum_{i=0}^{N-1} e^{-j\Phi_i} H\left(f - \frac{i+k+1}{N\tau}\right) \times \sum_{i'=0}^{N-1} e^{-j\Phi_{i'}} H\left(f - \frac{i'+k'+1}{N\tau}\right) e^{-j2\pi f t} df. \qquad (3)$$

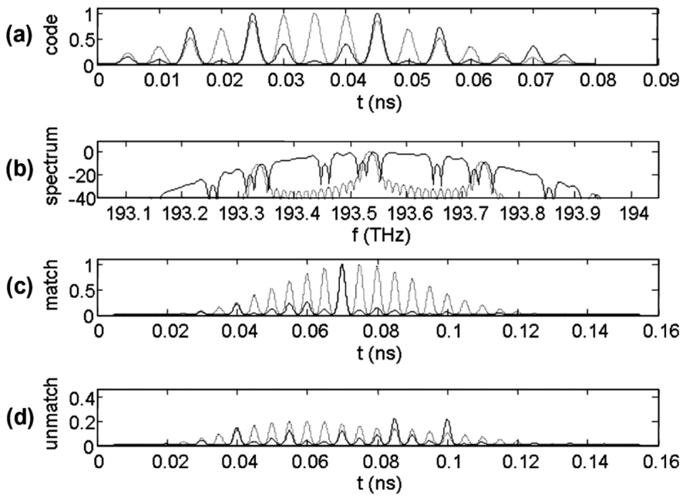

Fig. 4. (a) Intensity of the code; (b) spectral content; (c) auto-correlation (d); cross-correlation. Continuous line refers to a spectral-phase code with m-sequence phases and dotted line to a PSK code.

If $i+k=i'+k'$, the two subband channels overlap; otherwise, we can assume that their mutual product is negligible, obtaining

$$c_k(t) * c_{k'}(t) = \sum_{i=0}^{N-1} e^{-j\Phi_i} \cdot e^{-j\Phi_{i+k-k'}} \times \int H^2 \left(f - \frac{i+k+1}{N\tau}\right) e^{-j2\pi f t} df. \quad (4)$$

The integral in the previous expression is the auto-correlation function of the PSK code generated from the input i to the output k of the AWG-based E/D; we assume that this term is the same for all values of i and k.

The term $\sum_{i=0}^{N-1} e^{-j\Phi_i} \cdot e^{-j\Phi_{i+k-k'}}$ is the correlation between two phase-shift values: to obtain the same cross-correlation function between any two spectral-phase codes, we choose the phase values as a maximal length sequence (m-sequence) [9], [10], so that it is

$$\rho_{k-k'} = \sum_{i=0}^{N-1} e^{-j\Phi_i} \cdot e^{-j\Phi_{i+k-k'}} = \begin{cases} N, & k=k' \\ 1, & k \neq k' \end{cases}. \quad (5)$$

In this case, the cross-correlation between two different codes becomes

$$c_k(t) * c_{k'}(t) = \sum_{i=0}^{N-1} \int H_k^2 \left(f - \frac{i+k+1}{N\tau}\right) e^{-j2\pi f t} df \quad (6)$$

which is same for any choice of k and k'.

Fig. 4 shows the code, the corresponding spectral content, the auto-correlation and the cross-correlation signals of a spectral-phase code obtained using phases as an m-sequence of length $N = 15$. In this case, the ratio between auto- and cross-correlation peaks is 9 dB.

Therefore, an m-sequence is the optimal choice for the phase-shift values that allows us to obtain codes with the same detectability parameter, i.e., the ratio between the auto- and cross-correlation peaks is the same for all the codes generated by the device.

IV. Conclusion

We have presented an innovative configuration of a multiport E/D that is able to generate and process simultaneously a set of different spectral-phase codes. The architecture is based on a previous device that has been used in many OPS, OBS, and optical code-division multiple-access experiments [11], [12]. The new configuration includes a set of phase shifters and a splitter, and presents enhanced performance in terms of code recognition and network confidentiality. The auto-correlation function of the previous device has a triangular shape, while it presents a single short pulse in the new configuration. This feature enhances the cascadability of the E/D and reduces the beat noise, since it allows the use of time-gating or thresholders. Furthermore, to correctly detect a code, the receiver not only has to possess the matched decoder, but also the information about the phase values. Therefore, network security has been enhanced, since we add an additional degree of freedom to the code generation. In fact, the encoder generates a different code set family for each choice of phase-shift values, and the overall code cardinality is very large. We also found that the m-sequence is the optimal phase-shift distribution, because all the codes generated by the device have the same ratio between the auto- and the cross-correlation functions.

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