Complementarity: \( \sum_{j=1}^{N} C_{i,j}(i,j) = 0 \)

1 \( \leq i \leq M, r_1 \neq 0 \) and \( r_2 \neq 0 \)

Orthogonality: \( \sum_{j=1}^{N} C_{i,j}(i,j) = 0 \)

1 \( \leq i, k \leq M \) and \( i \neq k, V r_1, r_2 \)

where \( C_{i,j}(i,j) \) denotes the aperiodic correlation function between \( B_{i,j} \) and \( B_{k,j} \).

To obtain the required ZCZ arrays, a recursive formula is needed as shown below:

\[
A = \begin{bmatrix}
BB & (-B)B \\
(-B)B & BB
\end{bmatrix}
\]

where \( B \) denotes the matrix whose \( i,j \) entry is the negation of the \( i,j \) entry of \( B \). \( BB \) (or \( -B \)) denotes the matrix whose \( i,j \) entry is the concatenation of the \( i,j \) entry of \( B \) and the \( i,j \) entry of \( B \).

It is clear that the set \( A \) contains \( 2M \) arrays of order \( L_1 \times (2L_2 \times 2N) \). Let \( A^0 \) and \( A^1 \) be two arbitrary arrays, their correlation function satisfying

\[
R_{x,y}(r_1, r_2) = 0 \quad \text{for } 1 \leq s \leq 2M, r_1 < L_1, r_2 < L_2 + 1
\]

and \( r_1, r_2 \neq (0, 0) \)

\[
R_{x,y}(r_1, r_2) = 0 \quad \text{for } 1 \leq s \leq 2M, r_1 < L_1
\]

and \( r_2 < L_2 + 1 \)

That is, the set \( A \) is a ZCZ-((\( L_1, 2L_2 \times 2N \)), \( 2M, (L_1, L_2 + 1) \)) set with \( Z_{\text{CZ}} = (L_1, L_2 + 1) \). Obviously, the set \( A^1 \) is a ZCZ-((\( L_1, 2L_2 \)), \( 2N, (L_1, L_2 + 1, L_1) \)) set with \( Z_{\text{CZ}} = (L_1, L_2 + 1, L_1) \), where the superscript \( 1 \) denotes matrix transposition.

Construction (i): Based on a two-dimensional mutually orthogonal complementary set \( B \), one can construct a ZCZ-((\( L_1, 2L_2 \times 2N \)), \( 2M, (L_1, L_2 + 1) \)) set \( A \) with \( Z_{\text{CZ}} = (L_1, L_2 + 1) \) by employing eq. 6 directly.

Construction (ii): Denote the matrix \( A \) on the left hand side of eqn. \( 6 \) as \( A_0 \), which is also a mutually orthogonal complementary array set. Then, by replacing \( B \) with \( A_0 \) in eqn. \( 6 \), we can obtain a new ZCZ set \( A_1 \), i.e., ZCZ-((\( L_1, L_2 + 1 \)), \( 4M, (L_1, L_2 + 1) \)) set with \( Z_{\text{CZ}} = (L_1, L_2 + 1) \) and size \( 4M \). Similarly, from a ZCZ array set \( A_n \), we can construct recursively a new ZCZ set \( A_{n+1} \), i.e., ZCZ-((\( L_1, 2^{n+1}L_2 \)), \( 2^{n+1}M, (L_1, 2L_2 + 1) \)) set with \( Z_{\text{CZ}} = (L_1, 2L_2 + 1) \) and size \( 2^{n+1}L_2 \), where \( n = 2, 3, \ldots \)

Construction (iii): From matrix \( B \) in eqn. 3, if we construct a matrix \( A = [B_1, B_2] \)

then \( A \) is a ZCZ-((\( 2L_1L_2, 2N \times 2L_2 \)), \( M, (L_1, L_2 + 1) \)) set. Moreover \( A \) is also a mutually orthogonal complementary array set containing \( 2M \) sets, each set have \( 2N \) arrays of order \( 2L_1 \times 2L_2 \). We can also construct recursively a new ZCZ set \( A_n \) from \( A_n-1 \), where \( A_0 = A \), \( n = 1, 2, \ldots, \lg M \). Thus \( A_n \) is a ZCZ-((\( 2^{n+1}L_1L_2, 2^{n+1}M \times 2^{n+1}L_2 \)), \( M, (2^{n+1}L_1, 2L_2 + 1) \)) set with \( Z_{\text{CZ}} = (2^{n+1}L_1, 2L_2 + 1) \) and the same size \( M \).

Illustrative example: We conclude with an illustrative example ZCZ-((4, 32), \( 4, (4, 5) \)).

(i) We construct a mutually orthogonal complementary array set \( B \) with four arrays (refer to [3]):

\[
B_{11} = \begin{bmatrix}
+ & + & + & - \\
+ & + & - & + \\
- & + & - & + \\
- & + & - & + \\
\end{bmatrix}
\]

\[
B_{12} = \begin{bmatrix}
+ & + & + & - \\
+ & + & - & + \\
- & + & - & + \\
- & + & - & + \\
\end{bmatrix}
\]

(ii) Using construction (i), we can derive the following ZCZ array set \( A = \text{ZCZ-((4, 32), \( 4, (4, 5) \)) with } Z_{\text{CZ}} = (4, 5) \text{ and size } M = 4, \)

\[
A = \begin{bmatrix}
A_{[1]} & A_{[2]} & A_{[3]} & A_{[4]}
\end{bmatrix}
\]

where \( A_{[1]} = [B_{11}, B_{12}, B_{13}, B_{14}] \) and \( A_{[2]} = [B_{21}, B_{22}, B_{23}, B_{24}] \) denote the matrices whose \( i,j \) entry is the negation of the \( i,j \) entry of \( A \).

In conclusion, we can construct a class of ZCZ-((\( 2^{n+1}L_1L_2, 2^{n+1}M \)), \( 2^{n+1}L_2 \)), \( (4, 2^{n+1}L_2 + 1) \) set with \( Z_{\text{CZ}} = (4, 2^{n+1}L_2 + 1) \) and size \( 2^{n+1}L_2 \) by using construction (ii), a class of ZCZ-((\( 2^{n+1}L_1L_2, 2^{n+1}M \)), \( 2^{n+1}L_2 \)), \( (4, 2^{n+1}L_2 + 1) \) set with \( Z_{\text{CZ}} = (2^{n+1}L_2, 2^{n+1}L_2 + 1) \) and size \( 2^{n+1}L_2 \) by construction (iii). By considering the transposition matrix, the ZCZ-((\( 2^{n+1}L_1L_2, 2^{n+1}M \)), \( 2^{n+1}L_2 \)), \( (4, 2^{n+1}L_2 + 1) \) set with \( Z_{\text{CZ}} = (2^{n+1}L_2, 2^{n+1}L_2 + 1) \) and size \( 2^{n+1}L_2 \) can also be obtained.

It should be noted that the idea presented in this Letter can also be extended to a three-dimensional code set with cubic zero correlation zone. A four- or higher-dimensional ZCZ code construction is also possible, although no obvious geometrical sense exists.

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References

High sensitivity waveform measurement with optical sampling using quasi-phasematched mixing in LiNbO3 waveguide

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High efficiency (\( 1.7 \times 10^{-5} \text{W}^{-1} \)) waveform measurement is experimentally demonstrated using quasi-phasematched mixing in an LiNbO3 waveguide. A 160Gb/s optical waveform is observed with temporal resolution of 3.6 ps.

Introduction: Optical waveform measurement by optical sampling based on optical nonlinearity is a promising method for evaluating ultrahigh-speed optical time-division multiplexed (TDMA) transmis-
through difference-frequency mixing (DFM). In the experiment, a planar-lightwave circuit (PLC) to produce a second harmonic (SH) of the 1550 nm signal is characterized with two continuous wave light sources for the same wavelength and the phase-matching condition is satisfied over a 60 nm bandwidth. This device was first introduced to the PPLN waveguide. The authors would like to thank K. Itatani and K.-I. Sato for their encouragement.

Fig. 2 Static characteristics of PPLN

(a) Input power against output power characteristics
(b) Wavelength characteristics

Discussion: To improve temporal resolution of sampling, it is necessary to shorten the device length L. The L-dependence of the conversion efficiency η is η = L^2, and the L-dependence of the temporal resolution t is determined by the phase-matching bandwidth of the device for sampling pulses L. To obtain the temporal resolution of 1 ps, the device length should be reduced to 13 mm, which would reduce the conversion efficiency 1.9 x 10^-3 W^-1. This is still about ten times that of our previous report [3], so that optical sampling with better than 1 ps temporal resolution with high sensitivity is expected. As for the measurable wavelength range, this optical sampling system has a wide tuning range for the signal wavelength corresponding to the C-band and L-band. In this experiment, we changed the optical filter after the PPLN device for signal wavelengths shorter and longer than that of the sampling pulse. But by optimising the wavelength of the sampling pulse, it is possible to measure the waveform of both C-band and L-band signals without changing the filter, which enables realisation of a simple configuration for the optical sampling system.

Conclusion: We have shown the waveform measurement of a 160 Gbit/s signal with optical sampling using broadband, high efficiency quasi-phase-matched mixing in an LiNbO3 waveguide. The measurable signal wavelength range was 1535-1600 nm and the maximum conversion efficiency was 1.7 x 10^-3 W^-1. This sampling system will realise high sensitivity waveform measurements with temporal resolution better than 1 ps for > 100 Gbit/s OTDM signals.

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3.08 Tbit/s (77 x 42.7 Gbit/s) WDM transmission over 1200 km fibre with 100 km repeater spacing using dual C- and L-band hybrid Raman/erbium-doped inline amplifiers


3.08 Tbit/s (77 x 42.7 Gbit/s) WDM transmission over 1200 km fibre with 100 km amplifier spacing and 100 Gbit/s channel spacing is demonstrated. Error-free transmission of all 77 channels is achieved by employing dual C- and L-band hybrid Raman/erbium-doped inline amplifiers, experimental low dispersion slope TrueWave fibre, and forward error correction.

Introduction: With the increasing demand for transmission capacity on optical fibre trunk lines, ultra-long haul 40 Gbit/s per-channel all-optical transmission systems are now becoming very attractive [1-3], as they offer high signal spectral efficiency and large capacity with a smaller number of channels, at potentially lower cost. However, the design of typical terrestrial transmission systems at 40 Gbit/s line rate with 100 km amplifier spacing is challenging, since the launched power into both the transmission fibre and the dispersion compensating fibre (DCF) is limited owing to non-linearity related impairments. The low dispersion tolerance of 40 Gbit/s signals is also an important issue [4]. The dispersion slope of the transmission fibre and the dispersion compensating modules must be matched to yield a net accumulated dispersion of less than approximately ±0 ps/nm/km for all WDM channels.

In this Letter, we demonstrate transmission of 3.08 Tbit/s (77 x 42.7 Gbit/s) over 1200 km fibre with 100 km spans by employing dual C- and L-band distributed Raman amplification, experimental low dispersion slope TrueWave fibre, and forward error correction. The 3.08 Tbit/s comprises 40 100 Gbit/s spaced WDM channels in the C-band and 37 100 Gbit/s spaced WDM channels in the L-band. Error-free transmission of all 77 channels is achieved. Furthermore, low dispersion slope fibre and matched DCF allocate the need for any per-channel post-compensation in the C-band.

![Fig. 1 Experimental setup](image-url)

Experimental setup: Fig. 1 is a schematic diagram of the recirculating loop experimental setup. The WDM transmitters consist of a 40 DFB laser diodes (LD) in the C-band (1530.72-1561.82 nm), and 37 DFB LD in the L-band (1570.42-1600.6 nm) on the 100 Gbit/s-spaced ITU-T frequency grid. The C- and L-band channels are multiplexed separately by waveguide grating routers (WGR), and modulated by two LiNbO₃ Mach-Zehnder modulators (MZM) driven by 42.7 Gbit/s electrical NRZ signals. Electrical time-domain multiplexing (ETDM) is employed to generate the 42.7 Gbit/s signals from four 10.664 Gbit/s data streams, each consisting of 201 1 PRBS, 9853 Gbit/s data encoded with 55/239 Reed-Solomon FEC. For pre-compensation of dispersion and channel decorrelation during transmission, the C- and L-band WDM channels are transmitted through 370 - 353 ps/nm dispersion, respectively, prior to being amplified, then combined and launched into the transmission line.

![Fig. 2 Dispersion maps for C-band and L-band](image-url)