Code Generator for Optical ZCZ Sequence with Zero-Correlation Zone $2^z$

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1. Introduction

The optical direct sequence spread spectrum (DS-SS) system can be expected to enable high-speed communication using a wide band [1–3]. Multiple access interference (MAI) cancellation methods with the optical orthogonal code (OOC) or modified prime sequence code (MPSC) have been proposed in the optical code division multiple access (CDMA) system [4, 5]. The optical CDMA system using the optical zero-correlation zone (ZCZ) sequence set can detect the desired sequence without the MAI of undesired sequences, even if the synchronization is not perfect between users [6]. The ambiguity of synchronization is dependent on the size of ZCZ. The generation methods of the optical ZCZ sequence set with ZCZ sizes of 2, 4, and 8 have been implemented on a field-programmable gate array (FPGA) and compared. As a result, the proposed code generator can reduce the circuit size and operate faster than the conventional code generator.

2. Optical ZCZ Sequence Set with $ZCZ = 2^z$

2.1 Definition of optical ZCZ sequence set with $ZCZ = 2^z$

Let $a_{N}^{i,z}$ be a biphase sequence of length $N$, whose elements take 1 or −1, written as

$$a_{N}^{i,z} = (a_{N,0}^{i,z}, \ldots, a_{N,i}^{i,z}, \ldots, a_{N,N-1}^{i,z}), a_{N,i}^{i,z} \in \{1, -1\}$$

where $z$ is a non-negative integer, $j$ is a sequence number, and $i$ is an order variable and denotes $i$ mod $N$. Similarly, let $\hat{a}_{N}^{i,z,d}$ be a binary sequence of length $N$, whose elements take 1 or 0, written as

$$\hat{a}_{N}^{i,z,d} = \left(\hat{a}_{N,0}^{i,z,d}, \ldots, \hat{a}_{N,j}^{i,z,d}, \ldots, \hat{a}_{N,N-1}^{i,z,d}\right), \hat{a}_{N,j}^{i,z,d} \in \{0, 1\}$$

where $d \in \{1, 0\}$

Let $A^z$ be a set of pairs of the biphase sequence $a_{N}^{i,z}$ and the binary sequence $\hat{a}_{N}^{i,z,d}$, written as

$$A^z = \{(a_{N}^{0,z}, \hat{a}_{N}^{0,z,d}), \ldots, (a_{N}^{i,z}, \hat{a}_{N}^{i,z,d}) \ldots, (a_{N}^{M-1,z}, \hat{a}_{N}^{M-1,z,d})\}$$

Keywords: optical CDMA system, optical ZCZ sequence set, code generator, field-programmable gate array (FPGA)
where $M$ is the number of sequences in a sequence family and is called family size.

A periodic correlation function between the sequences $a^{i,j}_{N}$ and $\hat{a}^{i',j'}_{N}$ at shift $i'$ is defined by

$$
\rho_{a^{i,j}_{N}, \hat{a}^{i',j'}_{N}} = \sum_{i=0}^{N-1} a^{i,j}_{N} \hat{a}^{i',j'}_{N} \text{mod } N \quad (4)
$$

In this paper, the above correlation function $\rho_{a^{i,j}_{N}, \hat{a}^{i',j'}_{N}}$ is called the autocorrelation function for $j = j'$ and the cross-correlation function for $j \neq j'$. If the periodic auto- and cross-correlation functions satisfy

$$
\rho_{a^{i,j}_{N}, \hat{a}^{i',j'}_{N}} = \begin{cases} w & \text{if } i' = 0, j = j', d = 0 \\ -w & \text{if } i' = 0, j = j', d = 1 \\ 0 & \text{if } i' = 0, j \neq j' \\ 0 & \text{if } 1 \leq |i'| \leq 2^{z} \end{cases} \quad (5)
$$

with $w = \sum_{a_{N}=0}^{N-1} a^{i',j'}_{N} < N$, then the set $A^{l}$ is called an optical ZCZ sequence set [6] with the ZCZ size ZCZ = $2^{z}$. The optical ZCZ sequence sets are bounded by $M \leq N/(ZCZ + 1)$.

2.2 Construction of optical ZCZ sequence set

With ZCZ = $2^{z}$

A Hadamard matrix is needed for the construction of the optical ZCZ sequence set with ZCZ = $2^{z}$. The construction method of the optical ZCZ sequence set changes in accordance with the type of Hadamard matrix. For example, the Sylvester-type Hadamard matrix is used here because the generation method is simple. Let $H_{N_{1}}$ be the Sylvester-type Hadamard matrix of order $N_{1} = 2^{n_{1}}$ with $n_{1} \geq 2$, written as

$$
H_{N_{1}} = [h_{N_{1}}^{0}, \cdots, h_{N_{1}}^{N_{1}-1}]^{T} \quad (6)
$$

where the symbol $T$ denotes the matrix transposition, which is defined by

$$
H_{N_{1}} = H_{N_{1}} \otimes \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \quad (8)
$$

where the operation $\otimes$ denotes the Kronecker product, and $h_{N_{1}}^{i}$ is a Sylvester-type Hadamard sequence.

An element of the biphase sequence $a^{i,j}_{N_{1}} \in \{-1, 1\}$ of length $N = 2N_{1}$ is given by

$$
a^{i,j}_{N_{1}} = \begin{cases} h_{N_{1}}^{i,j} & ; 0 \leq i \leq \frac{N_{1}}{2} - 1 \\ -(-1)^{i+j} h_{N_{1}}^{i-j} & ; \frac{N_{1}}{2} \leq i \leq N - 1 \end{cases} \quad (9)
$$

where $i$ denotes $i \text{ mod } N$. If the Hadamard matrix is not the Sylvester-type Hadamard matrix, the negation position of Eq. (9) changes. The mean value of the biphase sequence $a^{i,j}_{N}$ is given by $\sum_{i=0}^{N-1} a^{i,j}_{N} = 0$ with $j \neq 0, 1$. Therefore, the biphase sequence $a^{i,j}_{N}$ is called a biphase balanced sequence. On the other hand, an element of the binary sequence $\hat{a}_{N}^{i,j} \in \{0, 1\}$ of length $N$ is given by

$$
\hat{a}_{N}^{i,j} = \frac{1 + (-1)^{j} a^{i,j}_{N}}{2} \quad (10)
$$

Let $A^{0}$ be a set of $(N/2 - 2)$ pairs of the biphase sequence $a^{i,j}_{N}$ and the binary sequence $\hat{a}_{N}^{i,j}$ of length $N = 2N_{1}$ except when $j = 0$ and 1. The periodic correlation function between $a^{i,j}_{N}$ and $\hat{a}_{N}^{i,j}$ is given by

$$
\rho_{a^{i,j}_{N}, \hat{a}_{N}^{i,j}} = \begin{cases} \frac{N}{2} & ; i' = 0, j = j', d = 0 \\ -\frac{N}{2} & ; i' = 0, j = j', d = 1 \\ 0 & ; i' = 0, j \neq j' \\ 0 & ; 1 \leq |i'| \leq 2^{z} \end{cases} \quad (11)
$$

Therefore, the above set of $M$ pairs of the biphase sequence $a^{i,j}_{N}$ and the binary sequence $\hat{a}_{N}^{i,j}$ is called an optical ZCZ sequence set with ZCZ = $2^{z} = 1$ and $M = N/2 - 2 + \log_{2}(ZCZ)$ mod 2 [8].

2.3 Construction of optical ZCZ sequence set

With ZCZ = $2^{z}$

The biphase sequence $a^{i,j}_{N}$ of length $N$ and the sequence number $j = 2k$, $k = 0, \cdots, \frac{N}{2} - 1$ are generated by

$$
a^{i,j}_{N} = (a^{i,j}_{N,0}, a^{i,j}_{N,1}, \cdots, a^{i,j}_{N,2^{z}-1}, a^{i,j}_{N,2^{z}+1}, \cdots, a^{i,j}_{N,2^{z}+2^{z}-1}, a^{i,j}_{N,2^{z}+2^{z}+1}, \cdots, a^{i,j}_{N,N-1}) \quad (12)
$$

Similarly, the biphase sequence $a^{i,j}_{N}$ of length $N$ and the sequence number $j = 2k+1$, $k = 0, \cdots, \frac{N}{2} - 1$ are generated by

$$
a^{i,j}_{N} = (a^{i,j}_{N,0}, a^{i,j}_{N,1}, \cdots, a^{i,j}_{N,2^{z}-1}, a^{i,j}_{N,2^{z}+1}, \cdots, a^{i,j}_{N,2^{z}+2^{z}-1}, a^{i,j}_{N,2^{z}+2^{z}+1}, \cdots, a^{i,j}_{N,N-1}) \quad (13)
$$

On the other hand, an element of the binary sequence $\hat{a}_{N}^{i,j}$ of length $N$ is given by Eq. (10). The periodic correlation function between $a^{i,j}_{N}$ and $\hat{a}_{N}^{i,j}$, except when $0 \leq j, j' \leq (z + 1) \text{ mod } 2$, is given by

$$
\rho_{a^{i,j}_{N}, \hat{a}_{N}^{i,j}} = \begin{cases} \frac{N}{2} & ; i' = 0, j = j', d = 0 \\ -\frac{N}{2} & ; i' = 0, j = j', d = 1 \\ 0 & ; i' = 0, j \neq j' \\ 0 & ; 1 \leq |i'| \leq 2^{z} \end{cases} \quad (14)
$$

Therefore, the above set of $M$ pairs of the biphase sequence $a^{i,j}_{N}$ and the binary sequence $\hat{a}_{N}^{i,j}$ is called an optical ZCZ sequence set with ZCZ = $2^{z} = 1, 2, \cdots$ and $M = \frac{N}{ZCZ} - 2 + \log_{2}(ZCZ) \text{ mod } 2$ [8].

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2.4 Examples

Let $H_4$ be the Sylvester-type Hadamard matrix of order 4, written as

$$
H_4 = \begin{bmatrix}
    h_{0,0}^0 & h_{0,1}^0 & h_{0,2}^0 & h_{0,3}^0 \\
    h_{1,0}^0 & h_{1,1}^0 & h_{1,2}^0 & h_{1,3}^0 \\
    h_{2,0}^0 & h_{2,1}^0 & h_{2,2}^0 & h_{2,3}^0 \\
    h_{3,0}^0 & h_{3,1}^0 & h_{3,2}^0 & h_{3,3}^0 \\
\end{bmatrix} = \begin{bmatrix}
    + & + & + & + \\
    + & + & + & + \\
    + & + & + & + \\
    + & + & + & + \\
\end{bmatrix}
$$

where + and − denote 1 and −1, respectively. Let $a_{16}^{i0}$ be a biphase sequence in an optical ZCZ sequence set with $Z_{cz} = 1(= 2^0)$ and $N = 8$. From Eqs. (8) and (9), the biphase sequence $a_{16}^{i0}$ is generated by a Hadamard sequence $h_4^j$ and is written as

$$
a_{16}^{i0} = (h_{0,0}^0, h_{1,0}^0, h_{2,0}^0, h_{3,0}^0, h_{0,1}^0, h_{1,1}^0, h_{2,1}^0, h_{3,1}^0, h_{0,2}^0, h_{1,2}^0, h_{2,2}^0, h_{3,2}^0, h_{0,3}^0, h_{1,3}^0, h_{2,3}^0, h_{3,3}^0) = (+, +, +, +, +, +, +, +, +, +, +, +, +, +, +, +)
$$

Let $a_{16}^{i1}$ be a biphase sequence in an optical ZCZ sequence set with $Z_{cz} = 2(= 2^1)$ and $N = 16$. From Eqs. (12) and (13), $a_{16}^{i1}$ is generated by the biphase sequence $a_{16}^{i0}$ with $Z_{cz} = 1$ and $N = 8$ and is written as

$$
a_{16}^{i1} = (a_{16}^{i0}, -a_{16}^{i0}, a_{16}^{i0}, -a_{16}^{i0}, a_{16}^{i0}, -a_{16}^{i0}, a_{16}^{i0}, -a_{16}^{i0}, a_{16}^{i0}, -a_{16}^{i0}, a_{16}^{i0}, -a_{16}^{i0}, a_{16}^{i0}, -a_{16}^{i0}, a_{16}^{i0}, -a_{16}^{i0})
$$

The mean value of the biphase sequence $a_{16}^{i1}$ is given by

$$
\sum_{i=0}^{15} a_{16}^{i1} = 0 \quad \text{with} \quad j \neq 0. \quad \text{Therefore,} \quad M = 16/2 - 2 + \lfloor \log_2(2) \mod 2 \rfloor = 3. \quad \text{From Eq. (10), the binary sequence} \quad \hat{a}_{16}^{i1,d} \quad \text{of} \quad d = 0, 1 \quad \text{and the sequence number} \quad j = 1, 2, 3 \quad \text{are written as}
$$

$$
\hat{a}_{16}^{11,0} = (+, +, +, +, +, +, +, +, +, +, +, +, +, +, +, +)
$$

The periodic autocorrelation function $\rho_{a_{16}^{i1,d}}^{j1}$, for $j = 1, 2, 3$ and $d = 0, 1$ is given by

$$
\rho_{a_{16}^{i1,d}}^{j1} = (8, 0, 0, -2, 4, -2, 0, -4, 0, -4, 0, -2, 4, -2, 0, 0)
$$

and the period cross-correlation function $\rho_{a_{16}^{i1,d},a_{16}^{i1,d'}}$, is given by

$$
\rho_{a_{16}^{i1,d},a_{16}^{i1,d'}} = (0, 0, 0, 2, 0, 0, 0, 2, 0, 0, 2, 0, 0, 2, 0, 0)
$$

From Eqs. (15) and (16), the periodic auto and cross-correlation functions satisfy Eq. (14).

3. Code Generator for Optical ZCZ Sequence with $Z_{cz} = 2^d$

3.1 Optical ZCZ-CDMA system

Figure 1 shows an optical ZCZ-CDMA system using an optical ZCZ sequence set. In transmitters, each code generator generates the binary sequence $\hat{a}_{16}^{i1,d}$ depending on the input data $d_j$ and the sequence number $j$ and sends it as the optical signal. This conversion from the sequences
to the optical signals occurs at electrical-to-optical (E/O) converters. The binary sequence elements 1 and 0 correspond to the on-off of light sources of the E/O converters, respectively.

A receiver converts the received optical signal to the electrical signal by an optical-to-electrical (O/E) converter. The received signal is correlated with the biphase sequence $a_{N}^{j,z}$ in a matched filter (MF). From Eq. (5), if the difference between the arrival times of signals from each transmitter is within $2^z$, the received data $\hat{d}_j$, can be detected by threshold detection without MAI.

When this system is implemented, as many code generators as light sources are necessary. Thus, reducing the size of the code generator is important.

### 3.2 Conventional code generator using ROM

Although the code generator can be constructed for any code by using ROM, the size of the circuit increases. A code generator using ROM is called a conventional code generator in this paper. The conventional code generator of the optical ZCZ-CDMA system uses a ROM that stores all the values of the optical ZCZ sequences. Note that the sequences stored in the ROM are binary sequences because these are used for transmitters in the optical ZCZ-CDMA system. The ROM address is generated by the combination of the input data $d$, the sequence number $j$, and the order variable $i$. Now, the order variable $i$ and the sequence number $j$ are expressed in a binary notation as:

$$i = \sum_{k=0}^{n-1} 2^k i_k, i_k \in \{1, 0\}$$

$$j = \sum_{k=0}^{m-1} 2^k j_k, j_k \in \{1, 0\}$$

where $n = \log_2 N$ and $m = \log_2 M$. Table 1 shows the memory map of ROM in a conventional code generator for the optical ZCZ sequence $\hat{a}_{N_i}^{j,z,d}$ of sequence length $N_i$, sequence number $j$ and $ZCZ = 2^z$. In addition, the order variable $i$ can be expressed as an up-counter because the order variable $i$ needs to be increased by one. From the above, Fig. 2 shows the conventional code generator for the sequence $\hat{a}_{N_i}^{j,z,d}$.

### 3.3 Proposed code generator without ROM

First, the construction of the code generator with $ZCZ = 1$, $z = 0$ is described. From Eq. (9), it can be seen that the binary sequence of the optical ZCZ sequence set is constructed by extending the Sylvester-type Hadamard sequence. Let $\hat{h}_{N_i}^{j,d}$ be the Sylvester-type Hadamard sequence whose elements are 1 or 0, written as

$$\hat{h}_{N_i}^{j,d} = \frac{1 + (-1)^i \hat{h}_{N_i}^{j,d}}{2}$$

Furthermore, the Sylvester-type Hadamard sequence $\hat{h}_{N_i}^{j,d}$ of length $N_i = 2^n$ is written as the following Boolean expression [7].

$$\hat{h}_{N_i}^{j,d} = d \oplus \sum_{k=0}^{n-1} x_{N_i}^{i_k \cdot j_k}$$

Here, the notation $\sum_{x_{OR}}$ means

$$\sum_{k=1}^{n} x_{OR} = x_1 \oplus x_2 \oplus \cdots \oplus x_n$$

In addition, the operations $\cdot$, $\oplus$ and (\) denote the logic operation AND, exclusive-OR (XOR) and NOT, respectively. The code generator of the binary sequence $\hat{a}_{N_i}^{j,z,d}$ of length $N = 2N_i$ and $z = 0$ is given by applying Eq. (20) to Eqs. (9) and (10). Therefore, the code generator is written as the following Boolean expression [7].

$$\hat{a}_{N_i}^{j,z,d} = d \oplus (\hat{h}_{N_i}^{j,d} \cdot i_{k-1}) \oplus \sum_{k=0}^{n-2} x_{N_i}^{i_k \cdot j_k}$$

The order variable $i$ of Eq. (22) can be expressed as an up-counter as with the conventional code generator. Thus,
Fig. 1 Optical ZCZ-CDMA system using an optical ZCZ sequence set of length $N$, family size $M$, $Z_{cz} = 2^z$ and input data $d_j$

the code generator of $\alpha_{N,i}^d$ can be constructed with only an up-counter and logic gates, without ROM.

Next, the construction of the code generator with $Z_{cz} = 2^z$, $z \geq 1$ is described. The optical ZCZ sequence with $Z_{cz} = 2^z$ is generated by applying the operation of Eqs. (12) and (13) to the sequence with $Z_{cz} = 2^{z-1}$. In other words, this means that the operation is applied $z$ times to the sequence with $Z_{cz} = 1$. The operation of Eqs. (12) and (13) is divided into two operations. First, the sequences with $Z_{cz} = 2^z - 1$ are interleaved. Second, the elements in which $i$ and $j$ are even numbers are negated. The sequence $\hat{\alpha}_{N,i}^{j,z,d}$, which is generated by applying the interleave operation $z$ times to the sequence with $Z_{cz} = 1$, is written as the following Boolean expression:

$$\hat{\alpha}_{N,i}^{j,z,d} = d \oplus (i_{z-1} \cdot i_z) \oplus \sum_{k=1}^{n_z-1} \sum_{i=2^k} \prod_{p=0}^{k} \left\{ i_p \oplus \left( \left\lfloor \frac{\ell}{2^p} \right\rfloor \mod 2 \right) \right\} \quad (23)$$

Additionally, the elements of Eq. (23) are negated by the second operation in the case that the following Boolean expression $s_{i,j,z}$ is equal to 1.

$$s_{i,j,z} = (i_0 \cdot j_0) \oplus \sum_{k=1}^{n_z} \sum_{\ell=2^k} \prod_{p=0}^{k} \left\{ i_p \oplus \left( \left\lfloor \frac{\ell}{2^p} \right\rfloor \mod 2 \right) \right\} \quad (24)$$

The notation $\prod_{\text{AND}}$ means

$$\prod_{k=1}^{n} x_k = x_1 \cdot x_2 \cdots x_n \quad (25)$$

From Eqs. (23) and (24), the binary sequence $\hat{\alpha}_{N,i}^{j,z,d}$ of length $N$ and $z \geq 1$ is written as the following Boolean
expression:
\[
\hat{a}_{Nz}^{i,j,d} = \hat{a}_{Nz}^{i,j,d} \oplus s_{i,j,z}
\]
\[
= d \oplus (i_{z-1} \cdot i_z) \oplus \sum_{k=1}^{\frac{N}{2}} (i_{k+1} \cdot j_k)
\]
\[
\oplus (i_{n-1} \cdot i_n) \oplus (i_n \cdot j_0)
\]
\[
\oplus \sum_{k=1}^{\frac{N}{2}} \sum_{\ell=2^k}^{\frac{N}{2}} \sum_{p=0}^{\frac{N}{2}} \{ i_p \oplus (\ell \cdot \frac{2^p}{2^\ell} \mod 2) \}
\]

As with the code generator of \( \hat{a}_{Nz}^{i,j,d} \), the proposed code generator of the sequence \( \hat{a}_{Nz}^{i,j,d} \) can be constructed of only an up-counter and logic gates. From Eq. (26), the code generator of the sequence \( \hat{a}_{Nz}^{i,j,d} \) is shown in Fig. 3.

For example, the proposed code generator for the optical ZCZ sequences of \( N = 64 \) and \( Z_{cz} = 4(= 2^2) \) is given by

\[
\hat{a}_{64z}^{i,j,d} = d \oplus (i_3 \cdot j_2) \oplus (i_1 \cdot j_1) \oplus (i_4 \cdot j_2)
\]
\[
\oplus (i_2 \cdot j_3) \oplus (i_0 \cdot j_0)
\]
\[
\oplus (i_0 \oplus 0) \cdot (i_1 \oplus 1)
\]

(27)

\[
= d \oplus (i_3 \cdot j_2) \oplus (i_1 \cdot j_1) \oplus (i_4 \cdot j_2)
\]
\[
\oplus (i_2 \cdot j_3) \oplus (i_0 \cdot j_0)
\]
\[
\oplus (i_0 \oplus 0)
\]

(28)

from Eq. (26). Note that \((i_n \oplus 0)\) and \((i_n \oplus 1)\) in Eq. (27) are \(i_n\) and \(i_n\), respectively. From Eq. (28), the code generator for the sequence \( \hat{a}_{64z}^{i,j,d} \) of length \( N = 64 \) and \( Z_{cz} = 4 \) is shown in Fig. 4.

4. Code Generator Implementation on FPGA

The conventional and proposed code generators for the optical ZCZ sequences of length \( N = 64, 128, 256, 512 \) and \( 1024 \), and \( Z_{cz} = 2, 4 \) and \( 8 \) have been implemented on a field-programmable gate array (FPGA). The FPGA corresponds to 51,840 logic elements (LEs), which are the basic building blocks of an FPGA, containing a 4-input look-up table, a register, and additional logic. The output bus-width is the number of output signal lines, and its size is 1 bit. Table 2 shows the specifications of code generators. Figures 5 and 6 show the number of LEs and the maximum clock frequency of code generators for the sequence of \( Z_{cz} = 2, 4 \) and \( 8 \), respectively.

The upper limit of the maximum clock frequency depends on the specification of FPGA. However, the maximum clock frequency itself depends on the structure of the circuit. The circuit design to reduce logic gates existing between registers is needed to improve the maximum clock frequency. In other words, although the maximum clock frequency can be improved by increasing the number of registers, the circuit size also increases. In the conventional code generator, a ROM is used, and it is composed of registers and multiplexers. Therefore, the circuit depth of the multiplexers increases as the sequence length increases; then the maximum clock frequency decreases. Furthermore, from Table 1, the number of ROM address patterns increases exponentially as the sequence length increases. Hence, the number of LEs also increases exponentially. In contrast, from Eq. (26) and Fig. 3, the proposed code generator does not use ROM, and the sizes of logic gates increase linearly as the sequence length increases. For this reason, even if the sequence length increases, the number of LEs is small and the maximum clock frequency remains high in comparison with the conventional code generator.

5. Conclusions

In this paper, we propose a new structure of a code generator for the optical ZCZ sequence of \( Z_{cz} = 2^2 \). The proposed code generator can be constructed using an up-counter and logic gates, without ROM. The conventional and proposed code generators are implemented on an FPGA, and the proposed code generator can reduce the number of logic elements and improve the maximum clock frequency compared with the conventional code generator.
Fig. 4 Proposed code generator for the optical ZCZ sequence of length \( N = 64 \), sequence number \( j \) and \( Zcz = 4 \)

Table 2 Specifications of code generators that are implemented on FPGA

| Reference sequences | optical ZCZ sequence set |
|---------------------|-------------------------|
| Sequence length \( N \) | 64, 128, 256, 512, 1024 |
| Zero-correlation zone \( Zcz \) | 2, 4, 8 |
| Output bus width | 1bit |
| FPGA | Altera APEX20KE EP20K1500EBC652-1X |
| Max. logic elements | 51, 840 |
| Max. pins | 488 |
| Analysis and synthesis tool | Altera QuartusII 8.1(64bit) |

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