

## Configuration of nonlinear couplers for creation of random optical multipulses

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### ABSTRACT

*In this paper, a configuration of nonlinear couplers with different coupling lengths is presented. Based on the influence of the transmission coefficient on the nonlinear index coefficient, the interval of the input intensity to generate overlap-transmission intensity at two output ports is determined. This behavior is simulated to confirm the connection of multiple nonlinear couplers as a configuration to generate random optical multi-pulses. The simulation results give us an opportunity to modulate laser pulses for information security of wireless or free-space laser communication.*

**Keywords:** Nonlinear coupler; Optical wireless communication; Laser pulses; Information security.

### 1. INTRODUCTION

In the fields of electronics and optics, signal pulses are commonly pre-processed before transmission. These signals may be modulated or split prior to transmission and recombined upon reception to ensure information security. In optics, a directional optical coupler is used to divide an input pulse into two output pulses with different peak intensities, according to a predetermined ratio [1–4]. However, since the output pulses retain the original input shape, ensuring information security is not feasible.

Unlike linear optical couplers, in nonlinear optical couplers, both the amplitude and the shape of the output pulses depend on the intensity of the input pulse. As a result, the output pulse becomes distorted and no longer maintains the same form as the input pulse [5–7]. Thanks to this property, nonlinear optical couplers have been studied and employed for pulse shaping and for separating pulses with different peak intensities [8–12].

This application is only viable when the intensity of the input pulse lies within the stable region of the transmission characteristic of the nonlinear coupler [13–15]. If the pulse intensity falls within the overlapping region of the transmission coefficient, the resulting output pulses will be random. In our previous works [16, 17], we demonstrated this behavior. However, our configuration was limited to a single coupler generating two output pulses.

To enhance information security, a single input signal pulse should ideally be split into multiple output pulses. In this work, we propose a configuration comprising three nonlinear couplers with various connection schemes to generate different sets of output pulses. Based on the operating principles and the transmission characteristics of nonlinear couplers, sets of random pulses were simulated for four different connection schemes. The obtained results suggest the potential application of random pulse generation in wireless optical communications.

### 2. PROPOSAL MODEL AND CONNECTION CASES

The model consists of three fiber-based nonlinear couplers, labeled A, B, and C, interconnected via switches  $K_1$  and  $K_2$ , as illustrated in figure 1. Each nonlinear coupler employs a guiding medium with a distinct nonlinear refractive index coefficient  $n_{nA}$ ,  $n_{nB}$ ,  $n_{nC}$  resulting in different transmission characteristics for each coupler.

Using the two switches  $K_1$  and  $K_2$ , the output ports (Ao1, Ao2, Bo1, Bo2) and input ports (Bi1,

Ci1) of two consecutive couplers can be either connected or separated. When the output port of one coupler is connected to the input port of another, the optical signal is transmitted from one coupler to the next. The remaining unconnected output port will direct the signal outward through the optical fiber.

There are four possible connection schemes:

1. Ao1 → Bi1 and Bo1 → Ci1
2. Ao2 → Bi1 and Bo1 → Ci1
3. Ao1 → Bi1 and Bo2 → Ci1
4. Ao2 → Bi1 and Bo2 → Ci1

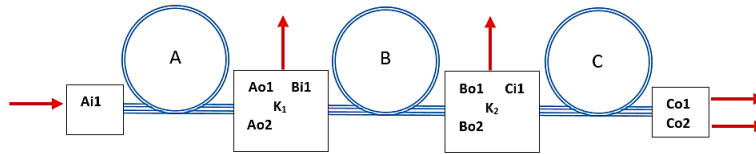


Figure 1. Proposed model.

*A, B, C – Nonlinear coupler; o-Output; i-Input; K<sub>1</sub> and K<sub>2</sub> -Optical switch.*

The four connection schemes produce four distinct sets of optical output signals, due to the differing transmission coefficients of each nonlinear coupler, which are dependent on the intensity of the preceding output signal. The output signals from couplers A, B, and C will exhibit phase delays relative to one another, with delay values determined by the lengths of the connecting optical fibers.

However, the two output signals from coupler C will remain in phase. The specific phase relationships and signal intensities will be determined during the practical design and implementation stage.

### 3. RESULTS AND DISCUSSION

#### 3.1. Transmission characteristics

As shown in Ref. [6, 7, 14], the transmission coefficients of SNC are given as following:

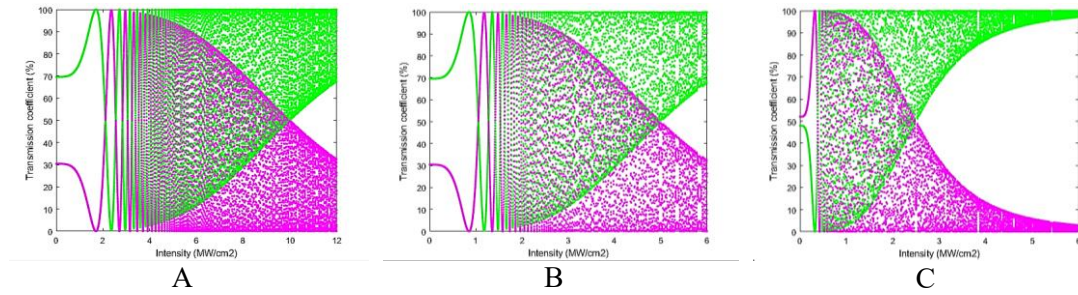
$$\eta_{thr-p}(l_c) = 1 - \frac{C_l^2}{C_{nl}^2 + C_l^2} \sin^2 \left( l_c \sqrt{C_{nl}^2 + C_l^2} \right) \quad (1)$$

$$\eta_{cr-p}(l_c) = \frac{C_l^2}{C_{nl}^2 + C_l^2} \sin^2 \left( l_c \sqrt{C_{nl}^2 + C_l^2} \right) \quad (2)$$

where  $\eta_{th-p}(l_c)$  and  $\eta_{cr-p}(l_c)$  are the transmission coefficients from through and cross-ports determined at the coupling length  $l_c$ , respectively;  $C_l$  is the linear coupling coefficient; and

$$C_{nl} = \frac{\pi c \epsilon_0 n_{nl}^2 I_{in}^2}{2\lambda} \quad (3)$$

is the nonlinear coupling coefficient; where,  $\lambda$  and  $c$  are the wavelength and velocity of the light,  $\epsilon_0 = 8.8541878128 \times 10^{-14}$  F/cm is the permittivity constant of vacuum,  $n_{nl}$  is the nonlinear coefficient of refractive index,  $I_{in} = I_{in}(l=0)$  is the input intensity of the optical field at input port. In this model, we choose  $l_c = 200$  m,  $n_{nlA} = 0.5 \times 10^{-8}$  cm<sup>2</sup> / W,  $n_{nlB} = 1 \times 10^{-8}$  cm<sup>2</sup> / W,  $n_{nlC} = 2 \times 10^{-8}$  cm<sup>2</sup> / W,  $\lambda = 1.06$  μm and  $C_l = 0.05$  cm<sup>-1</sup>. The transmission characteristics of the three couplers are numerically calculated and simulated as shown in figure 2.



**Figure 2.** Transmission characteristics of nonlinear couplers with different nonlinear coefficients of refractive index: A with  $n_{nlA} = 0.5 \times 10^{-8} \text{ cm}^2 / W$ ; B with  $n_{nlB} = 1 \times 10^{-8} \text{ cm}^2 / W$ ; C with  $n_{nlC} = 2 \times 10^{-8} \text{ cm}^2 / W$ .

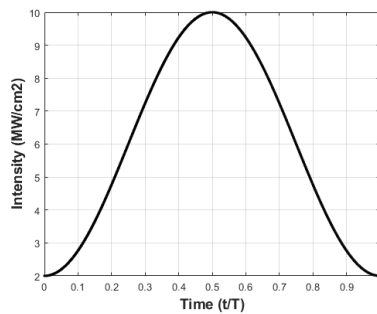
It is clearly observed that the beginning input intensity and the width of the region overlap interval is proportional inversely to the index nonlinear coefficient. For coupler A, this intensity marks the beginning of the overlap region with  $I_{entA} = 2.1 \times 10^6 \text{ W} / \text{cm}^2$  and width of the region overlap  $\Delta I_{ovelA} = 8 \times 10^6 \text{ W} / \text{cm}^2$ , Similarly, for coupler B, it is  $I_{entB} = 1.1 \times 10^6 \text{ W} / \text{cm}^2$  and  $\Delta I_{ovelB} = 4 \times 10^6 \text{ W} / \text{cm}^2$ , and for coupler C, it is  $I_{entC} = 0.7 \times 10^6 \text{ W} / \text{cm}^2$  and  $\Delta I_{ovelC} = 1.5 \times 10^6 \text{ W} / \text{cm}^2$ . Based on their characteristics, we can select an input signal with an intensity oscillating within the boundaries of the overlap intensity region.

### 3.2. Random output multi-pulse

First, for simplicity, we assume a monotonic pulse at the input port described by the following function:

$$I_{in} = I_{ave} + \frac{\Delta I_{ovel}}{2} \sin\left(\frac{2\pi t}{T} + \varphi\right) \quad (4)$$

where  $I_{ave} = (I_{ent} + I_{exit})/2$  is the average intensity, with  $I_{ent}$ ,  $I_{exit}$  are the input intensities at the beginning and end of the overlap region,  $\Delta I_{ovel} = I_{exit} - I_{ent}$  is the width of the region overlap, respectively. As is well known, the output intensity of each coupler is lower than its input intensity. Therefore, to ensure that the peak intensities of the output pulses from the preceding couplers remain within the overlap region of the subsequent coupler, we select  $I_{av}$  and  $I_m$  corresponding to the largest overlap intensity region. In the proposed model, this pulse serves as the input to coupler A. Based on the results shown in figure 2, we choose  $I_{ave} = 6 \times 10^6 \text{ W} / \text{cm}^2$  and  $\Delta I_{ovel} = 8 \times 10^6 \text{ W} / \text{cm}^2$ . Substituting these into equation (3), the input pulse at port A<sub>i</sub> is illustrated in figure 3.



**Figure 3.** Input pulse in port A<sub>i</sub>.

Next, we will simulate the four output pulses corresponding to four different connection configurations. The first configuration is Ao1-Bi1 and Bo1-Ci1. The output pulses appear at the four output ports Ao2, Bo2, Co1, and Co2.

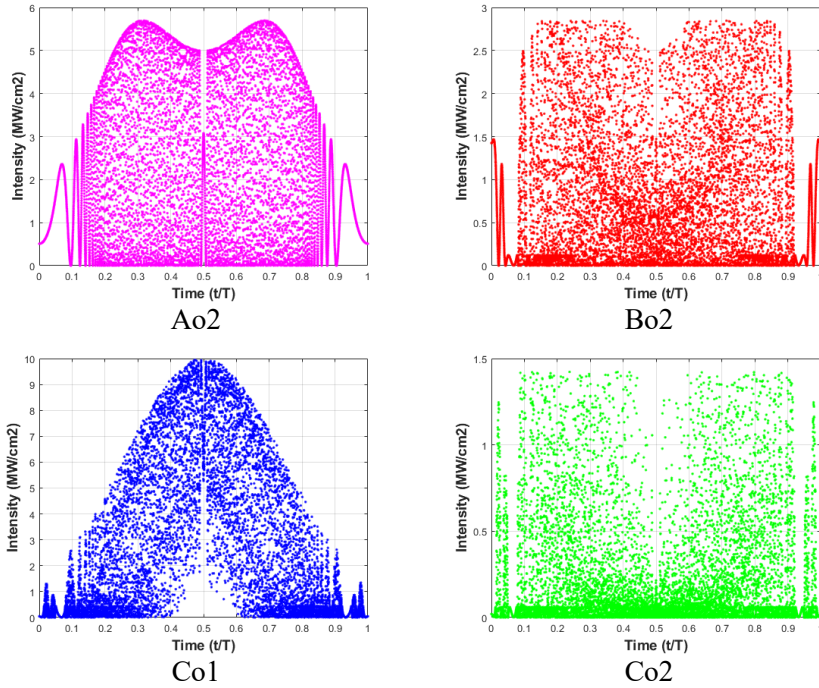


Figure 4. Output pulses at ports for the first case.

According to configuration 2: AO2-BI1, BO1-CI1

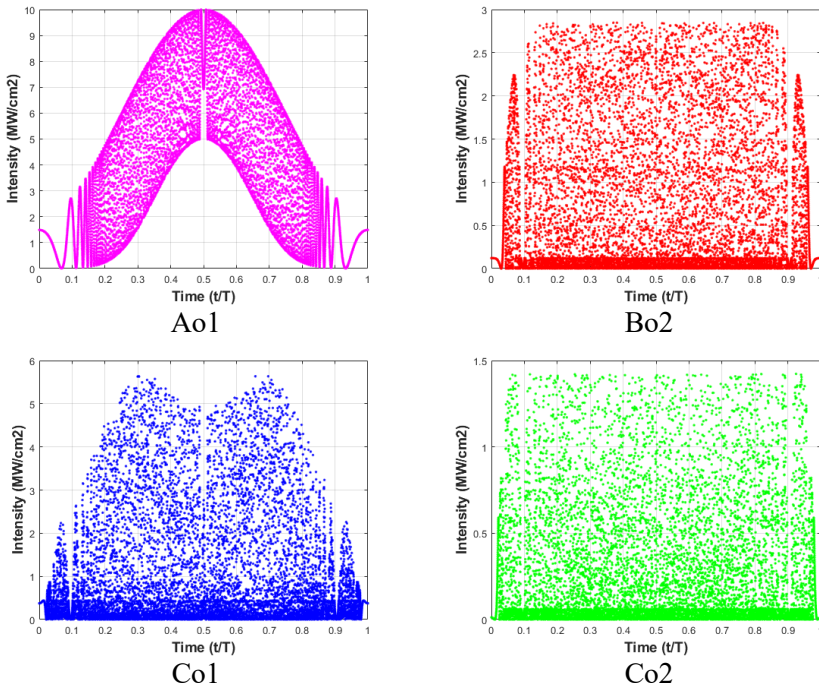


Figure 5. Output pulses at ports for the second case.

In configuration 3: AO1-BI2, BO2-CI1:

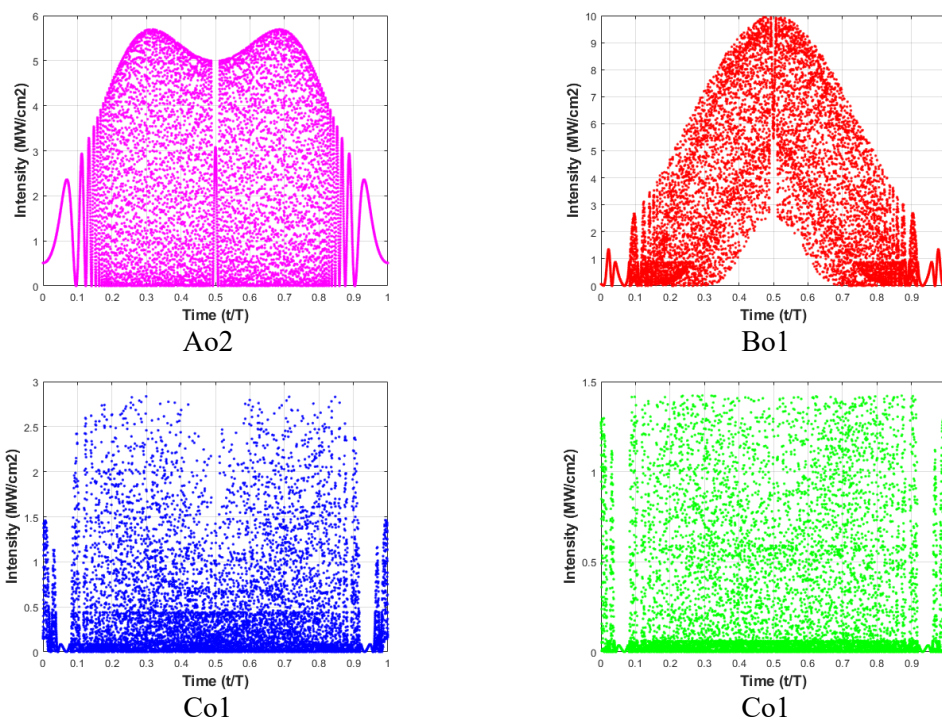


Figure 6. Output pulses at ports for the third case.

and configuration 4: AO2- BI1, BO2-CI1

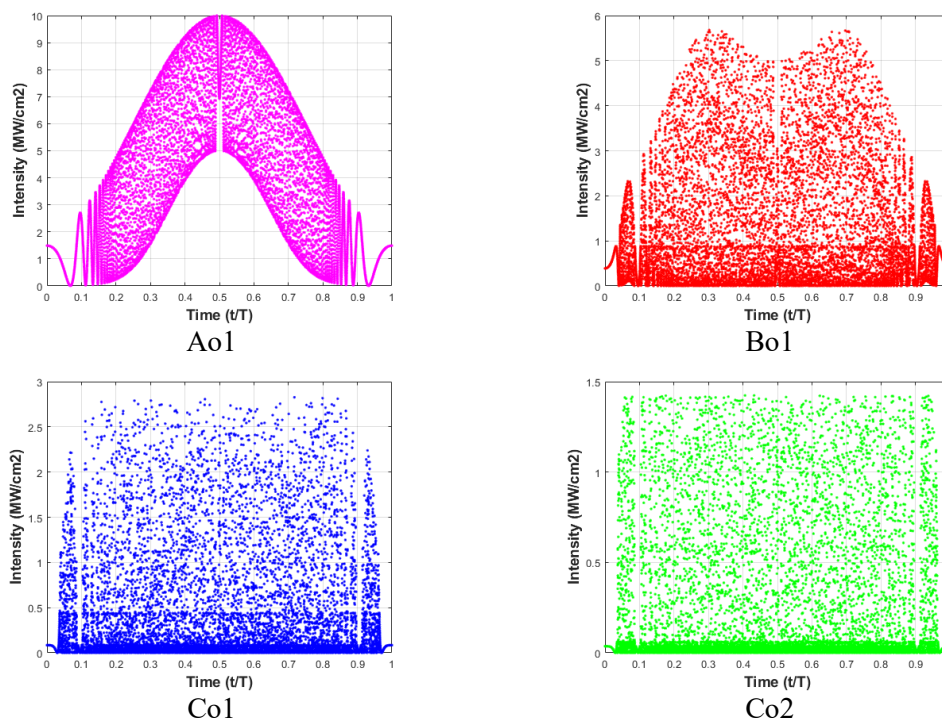


Figure 7. Output pulses at ports for the fourth case.

From the results shown in Figures 4, 5, 6, and 7, we observe that:

- i) The output pulses no longer maintain a single-valued curve but become band pulses;
- ii) The shape of the output pulses no longer retains the form of the input pulse;
- iii) The four output pulses exhibit completely different shapes;
- iv) The sets of four pulses vary distinctly across configurations.

Therefore, it can be inferred that the integration of multiple couplers enables the division of a single monotonic pulse into a collection of random band-limited pulses. This approach offers promising potential for enhancing information security by transmitting signals not as a single pulse, as illustrated in figure 1, but as a set of four pulses generated through the proposed configuration.

#### 4. CONCLUSIONS

We have proposed a configuration consisting of three nonlinear couplers with different transmission characteristics to generate four random-like pulses from a single monotone input pulse. The results show that, with four different connection schemes enabled by switching mechanisms, four distinct sets of output pulses are produced. These four configurations, combined with the randomness in the output pulse shapes, contribute to enhancing the security of the transmitted signal.

These findings serve as a foundation for designing an optical signal modulation system for free-space transmission, with the aim of improving the security of communication and the control of aerial or flying devices.

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### **TÓM TẮT**

#### **Cấu hình bộ ghép phi tuyến tạo các xung quang ngẫu nhiên đa xung**

Trong bài báo này, một cấu hình của các bộ ghép phi tuyến với các chiều dài ghép khác nhau được trình bày. Dựa trên ảnh hưởng của hệ số truyền đối với chiết suất phi tuyến, cường độ đầu vào để tạo ra sự chông lán cường độ truyền tại hai cổng đầu ra được xác định. Đặc tính này được mô phỏng để kiểm chứng tính khả thi của việc kết nối nhiều bộ ghép phi tuyến thành một cấu hình có khả năng tạo ra các xung quang ngẫu nhiên đa xung. Kết quả mô phỏng mang đến cơ hội điều chế các xung laser để bảo mật thông tin trong truyền thông laser không dây hoặc qua không gian tự do.

**Từ khóa:** Bộ ghép phi tuyến; Truyền thông quang không dây; Xung laser; Bảo mật thông tin.