$1 \times N$ dynamic optical coupler based on Dammann gratings

Caihui Di (底彩慧)[1,2] and Changhe Zhou (周常河)[1]

[1]*Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800*

[2]*Graduate School of the Chinese Academy of Sciences, Beijing 100039*

We present two novel $1 \times N$ dynamic optical couplers that are based on Dammann gratings to achieve dynamic optical coupled technology. One is presented by employing a specially designed Dammann grating that consists of the Dammann-grating area and the blank area. The other is developed by using two complementary even-numbered Dammann gratings. The couplers can achieve the function conversion between a beam splitter and a combiner according to the modulation of the gratings. We have experimentally demonstrated 1×8 dynamic optical couplers at the wavelength of 1550 nm. The experimental results and the analyses are reported in detail.

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Driven on the fast development of fiber-to-home project, there is a strong need for the new approach to achieve the dynamic coupling system with a large number of splitting branches[1,2]. Many types of coupling technologies[3−5] have been limited to the certain applications because of several practical issues, e.g., polarization dependence, wavelength dependence, and insensitivity against temperature dependence, especially in the case of a large number of splitting branches.

As a potential solution to this problem, Pan *et al.* first proposed a new broadband $1 \times N$ fiber coupler employing diffractive optical elements (DOEs)[6]. But their device only can function as a beam splitter and not perform dynamic coupling.

In this paper we present two novel $1 \times N$ dynamic optical couplers based on Dammann gratings, which can realize the dynamic function of either a beam splitter or a combiner according to the modulation of the gratings. The advantages of Dammann couplers include high efficiency and uniformity, low loss, compact size, and no added polarization dependence or insensitivity against temperature dependence. And they have the potential to be applied to splitting a large array, e.g., 8×16 array and 64×64 array.

Dammann gratings are actually binary surface-relief gratings for array illumination in the Fourier-transforming plane[7,8]. More progresses have been made in Dammann gratings[9−13]. Dammann grating requires a set of phase transitional points to characterize the binary-phase surface profile. The distribution of transparency in a rectangle cell can be represented by

$$t_k(x) = \mathrm{rect}\Big[\frac{x - (x_k + x_{k-1})/2}{x_k - x_{k-1}}\Big], \qquad (1)$$

where x is the distance of the phase transitional point, x_k is the distance of the kth transitional point. And the intensity for the nth spectra is

$$I_n = \left(\frac{1}{n\pi}\right)^2 \left\{ \left[\sum_{k=1}^{K} (-1)^k \sin\alpha_k \right]^2 + \left[1 + \sum_{k=1}^{K} (-1)^k \cos\alpha_k \right]^2 \right\}, \qquad (2)$$

where $\alpha_k = 2n\pi x_k$.

Dammann grating can be classified as odd-numbered Dammann grating and even-numbered Dammann grating. Furthermore an even-numbered Dammann grating has the unique phase distribution of π phase inversion every half a period that means they can be split into two parts. The special phase structure of the even-numbered Dammann grating leads to the absence of even-order spots including the zeroth-order and the only presence of odd-order spots in the spectrum.

The schematic structure is shown in Fig. 1. The configuration mainly includes a light source, an input fiber array, a shifter, a light power detector, a specially designed phase component, an output lens, and an output fiber array. The phase component is placed at the front focal plane of the output lens. The output fiber array is placed at the rear focal plane of the output lens. Using self-collimating lenses ensures high diffraction efficiency and good uniformity because of the collimation and expansion of the light beams. In the first device we divided a conventional even-numbered Dammann grating into two gratings with the same phase distribution $\phi_{Dam}(x_k)/2$. When there is no shift between the two phase plates, they equal to a normal even-numbered Dammann grating. The collimated light is diffracted into N spots with equal intensity. The N diffracted light outputs are focused by the output lens to the N output fibers. When there is an accurate shift of a half-period between plates, the total phase difference reduces to zero; the collimated light will be coupled only into the fiber that is located in the center. In the second device, we utilized a specially designed Dammann grating that consists of the Dammann-grating-distributing area and the

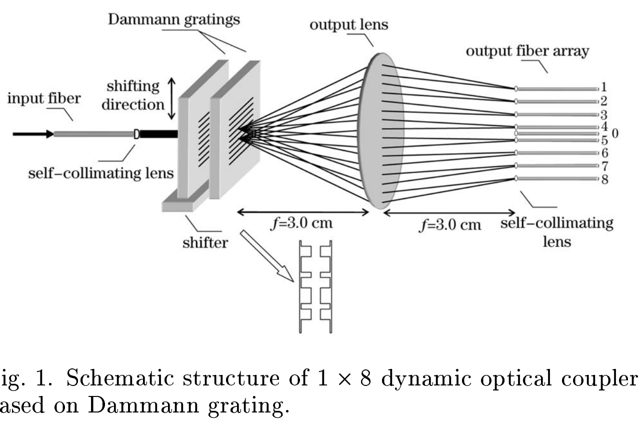

Fig. 1. Schematic structure of 1×8 dynamic optical coupler based on Dammann grating.

blank area. The principle is same to the dual Dammann grating approach. When the collimated beams entirely impinge on the Dammann-grating area of the plate, they are diffracted into spots with equal intensity. When the collimated beams entirely impinge on the blank area of the plate, the collimated light will be coupled only into the fiber that is located in the center. That is to say, the two couplers can perform as either a beam splitter or a combiner in principle and can be switched between both of them.

In the experiment, we employ 1×8 even-numbered Dammann gratings. The gratings are produced with microelectronic-lithography technology and the wet-chemical-etching method. The fabrication errors have been analyzed in Ref. [11].

Figure 2 shows the diffractive light spots when the couplers function as 1×8 splitters. Channels 1, 2, 3, 4, 0, 5, 6, 7, 8 in Fig. 1 are corresponding to orders −7, −5, −3, −1, 0, +1, +3, +5, +7 in Fig. 2. The small redundant even-order spots in Fig. 2 are mainly due to the fabrication errors of the wet-chemical-etching process[11]. The groove-depth error and the etched side error at the transitional-point edge will increase the zero-order spectral intensity and produce the redundant even-order light spots between two odd-order spots. The perfect Dammann gratings will not generate the unwanted diffraction orders.

When the systems work as a splitter, measured insertion losses are given in Fig. 3, together with the optimal theoretical insertion losses and the ideal results without

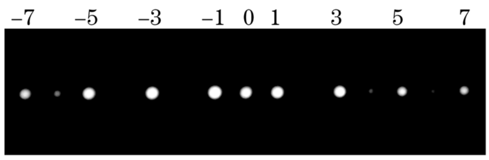

Fig. 2. Light spots taken on the rear focusing plane of the output lens with an infrared charge-coupled device (CCD) camera when our couplers work as a splitter.

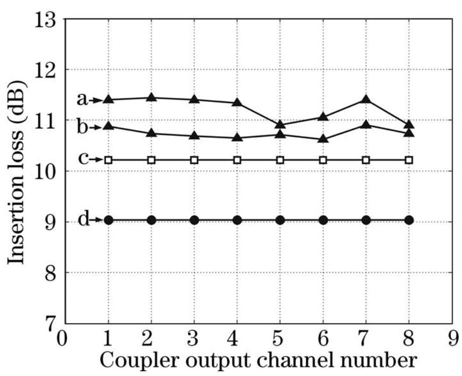

Fig. 3. Comparison of the measured insertion losses of (a) the dual gratings coupler and (b) the single grating coupler with (c) the optimal theoretical insertion losses and (d) the ideal results without any loss.

any loss. It can be seen that both of the dynamic optical couplers achieve good uniformity, which are a little larger than the optimal theoretical data and the ideal data. The insertion loss of around 11 dB for 8 channels is quite close to the experimental result reported by Pan *et al*.[6]. This excellent result is due to the structure of an even-numbered Dammann grating that has high diffraction efficiencies, the use of fiber lens collimators and the accurate alignment of the multi-output fiber array.

The insertion-loss-averaged value is 10.8 dB for experiment and 10.2 dB for numerical optimized data. It leaves about 0.6 dB (from 10.8 to 10.2 dB) insertion loss to improve. And we realize that there is a stringent requirement for spatial alignment of two complementary gratings for the dual Dammann gratings coupler. But this requirement does not exist in the single grating coupler.

In conclusion, we have presented two novel designs for $1 \times N$ dynamic optical couplers based on Dammann gratings. Two systems can realize the dynamic function between a beam splitter and a combiner according to the modulation of gratings. We have experimentally demonstrated high performance of 1×8 dynamic couplers. The experimental results presented in this paper demonstrate the unique advantages of Dammann-grating-incorporated systems for dynamic optical coupling of a large fiber array. Also they can easily be developed into other circular forms[12] and the two-dimensional (2D) form by employing 2D Dammann gratings.

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