PLC-Based Pulse-Train Generators

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***Abstract*—Novel planar-lightwave-circuit-based pulse-train-generator devices designed for use as repetition-rate multipliers are experimentally investigated. In addition to arrayed waveguide grating-based pulse-train generators and loss-engineered devices which have been previously demonstrated, novel excitation-engineered structures are described which illuminate design constraints that impact the practical implementation of various device designs.**

***Index Terms*—Planar waveguides, pulse generation, pulse-shaping methods, waveguide arrays.**

I. Introduction

MINIATURIZATION and loss minimization have fueled the development of planar lightwave circuits (PLCs), where semiconductor industry initiated tools (namely photolithography and reactive-ion etching) are applied to the fabrication of optical devices [1]–[3]. PLC-based fabrication is frequently employed in a wide range of devices such as power splitters, tapped delay lines, and arrayed waveguide gratings (AWGs). Although the range of applications utilizing PLC-based devices is enormous, the focus of this paper will be on experimental demonstrations of PLC-based devices designed for optical pulse repetition-rate multiplication applications.

Each repetition-rate multiplier device, shown schematically in Fig. 1, will consist of a splitter, an array of waveguides, and a combiner. The splitter directs light into each guide of the waveguide array. The waveguide array has a constant length difference between adjacent waveguides to temporally separate the pulses that will make up the output pulse sequence. The combining region is used to collect light from all the guides in the waveguide array and combine the temporally separated pulses onto one or more output channels. Note that it is not strictly required that the guides making up the waveguide array are kept in phase. As is well known, when the guides making up the waveguide array are kept in phase, the device will have a sharply peaked periodic spectral passband with free spectral range equal to the inverse of the delay increment per guide [4], [5]. This is the basis for array waveguide grating demultiplexer technology. However, from the perspective of the output temporal intensity profile, the phase of the waveguide-array guides is irrelevant. The output consists of a train of temporally separated pulses where each output pulse can be associated with a specific guide in the waveguide array—the so-called "one-guide, one-pulse" design methodology [6].

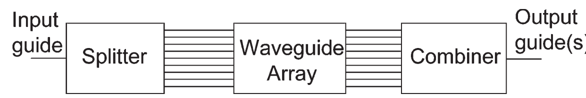

Fig. 1. Schematic diagram of the general repetition-rate multiplier device.

In previous work, we employed loss engineering within the waveguide array in order to generate trains of output pulses with nearly the same optical power [6], [7]. AWG structures combined with fixed [7] or programmable [8], [9] external means for controlling guide-by-guide loss can also be used for this purpose. In this paper, we discuss excitation engineering where the splitter/combiner regions are tailored to produce the desired output temporal profile. The loss engineering is implemented by inserting an excess loss within the waveguide array while the excitation engineering controls the splitting (and combining) profiles at the interface of the waveguide array.

The experimental work presented here will focus on various excitation-engineered PLC devices that will serve to convert a single short input pulse into a burst of 16 pulses separated by 1.5625 ps (spacing appropriate for a 640-GHz repetition-rate output). The impact of various splitter/combiner region designs will be investigated. We will show that the overall temporal window of the device output (i.e., the degree of "flatness" of the output pulse train) is determined by the temporal-window functions of both the splitter and combining regions. To our knowledge, this paper is the first to directly address the individual role of both the splitter and the combiner in determining the temporal-window function of the PLC pulse-train generator.

II. Experimental Configuration

Before discussing the various device configurations explored in this paper, it is relevant to present the experimental configuration utilized to characterize the response of these devices. A passively modelocked erbium fiber laser [10] generating ~75-fs pulses at 50-MHz repetition rate centered at 1575 nm is used to characterize the time-domain response of the devices. The output of the fiber laser is split into "signal" and "reference" arms, and all fiber paths are constructed to be dispersion compensated with an appropriate combination of single-mode and dispersion-compensating fiber (DCF). The "reference" arm goes directly to a free-space cross-correlation apparatus, where it is used to measure the temporal profile of the "signal" arm after going through the device under test.

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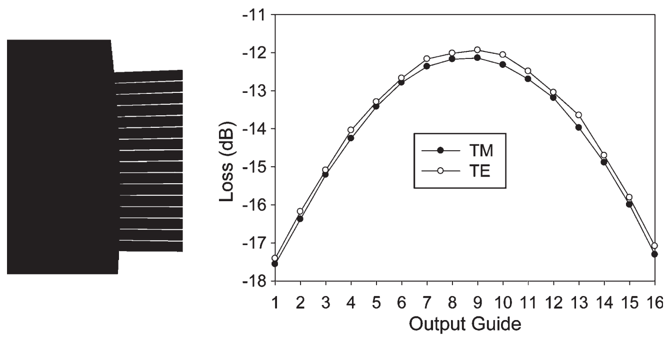
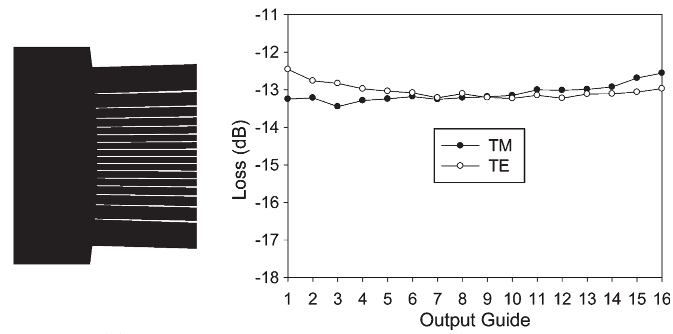


(a) (b)

Fig. 2. (a) Schematic representation of the output end of the conventional (AWG-like) splitter. (b) Loss as a function of guide number for CW excitation.



(a) (b)

Fig. 3. (a) Schematic representation of the output end of the funnel splitter. (b) Loss as a function of guide number for CW excitation.

The devices are bare PLC chips fabricated in a standard NEL silica-on-silicon process [1], which are mounted on a home-made vacuum chuck. Fiber coupling is performed with high-precision manual five-axis translators; index-matching fluid is applied in all cases. Typical fiber-coupling losses to test waveguides using this manual apparatus with short laser pulses are less than 2 dB. The laser signal output is connected to a polarization controller and fiber polarizer with polarization-maintaining (PM) fiber output, which is then directed to the PLC input. This allows the impact of varying the device launch polarization orientation to be investigated. The device input stage has an extra degree of freedom compared to the output stage so that the orientation angle of the PM fiber can be adjusted at the input face of the device.

III. Splitter/Combiner

Prior to exploring the complete optical pulse-train repetition-rate multiplier module, splitter/combiner region designs will be discussed. Two designs will be focused on: conventional (AWG-like) and funnel style [11] splitter/combiners. Viewed as a splitter, all designs will consist of one single-mode input waveguide, a slab waveguide region, and 16 approximately single-mode output guides. The differences between the splitter designs are in the specifics of the slab waveguide and the interface between the slab and output waveguides. All of these devices will also function to combine signals from multiple channels onto a single output—i.e., they function "backward." We also have investigated multimode-interference devices [12] as time-domain pulse splitters; however, their significant spectral dependence in the optical splitting ratio [13] and large physical size make this design splitter/combiner impractical for pulse-train repetition-rate multipliers.

A. Conventional

What we are describing here as a "conventional" splitter, the output end of which is shown schematically in Fig. 2(a), is a slab region where the input and output ends are configured on a Roland circle as is done in AWG devices generally used as channel multiplexers/demultiplexers in wavelength-division-multiplexed systems. Within the slab region, the light from the input guide is confined in the vertical direction with the same mode field diameter as the input guide. In the horizontal direction, the mode is allowed to expand and fill the aperture of the waveguide array at the output face of the slab region. The guides at the output face are all in the same dimension as the input guide (i.e., single mode), and the guides are closely spaced in order to maximize power transfer from the input guide to the output guides. Since the light spreads, but retains a Gaussian distribution in the slab waveguide, the power distribution in the various output guides is not equal; the output guide directly across from the input will have the highest output power, and the power coupled into each guide will drop with the distance from the center. This situation is confirmed in Fig. 2(b) that shows the output-power distribution of the 16 output guides when a continuous-wave (CW) source is used for excitation. Note also that an excitation with two orthogonal polarization states produces nearly identical results at the output indicating polarization independence for this splitter implementation.

For this splitter/combiner design, in order to equalize the power in each output guide, as would be desirable for repetition-rate multiplication applications (where each output pulse is associated with a specific guide in the waveguide array), one of the two schemes (or a combination of the two) could be employed which we refer to as "loss-engineering." Either the output guide coupling could be partially disrupted, or excess loss could be inserted within the waveguide array. In order to minimize the excess loss associated with generating a train of equal amplitude pulses via loss engineering, an alternative splitter/combiner design will be considered next.

B. Funnel

The funnel splitter [11], the output end of which is shown schematically in Fig. 3(a), is a modification of the conventional splitter discussed above. The input and slab waveguide regions are identical to the conventional splitter. At the output face of the slab waveguide, the waveguide apertures are expanded as the distance from the center output guide is increased in order to equalize the amount of light coupled into each output guide. We refer to this process as "excitation engineering." These widened waveguides are adiabatically tapered to the width of the center (single mode) guides over a length of a few millimeters in the waveguide array. Table I indicates the waveguide widths at the boundary of the slab region and the waveguide array and normalized power splitting ratio indicated by beam-propagation-method (BPM) simulations. Although the

TABLE I
FUNNEL SPLITTER/COMBINER GUIDE WIDTH AND NORMALIZED POWER SPLIT OBTAINED FROM BPM SIMULATIONS

Guide #	Width (μm)	Power Split
1	35.7	0.84023
2	17.2	0.83619
3	11.6	0.83634
4	9.4	0.84292
5	8.2	0.83452
6	7.5	0.83562
7	7.2	0.83768
8	7.0	0.84330
9	7.0	0.84330
10	7.2	0.83768
11	7.5	0.83560
12	8.2	0.83451
13	9.4	0.84291
14	11.6	0.83635
15	17.2	0.83619
16	35.7	0.84022

waveguide funnels have been utilized before to engineer the spectral passband of PLC-based wavelength demultiplexers, we report here, for the first time to our knowledge, the use of these devices as the time-domain pulse-train generators.

Fig. 3(b) shows the output power from each of the 16 output guides when a CW source is used for excitation. Excellent power uniformity, low polarization dependence, and low excess loss are apparently validating the excitation-engineering approach. We attribute the measured variability in splitting ratio (less than 1 dB) primarily to the difficulty in precisely modeling the waveguide character in the funnel regions.

IV. COMPLETE PULSE REPETITION-RATE MULTIPLIER: TIME-DOMAIN DESIGN

The description of the output-power variation of the splitter/combiner designs shown above is critical to the overall temporal profile of the complete repetition-rate multiplier device. The splitter serves to excite the various guides making up the waveguide array; in the limit where the input pulses are shorter than the delay increment per guide within the waveguide array, the waveguide array serves to temporally separate the pulses that will make up the output pulse train; the combiner merges the temporally separated pulses onto the output guide. While it may be possible to design the repetition-rate multiplier device using a frequency-domain description, as would be employed for AWG devices, this design methodology relies critically on the various guides within the waveguide array being in-phase. Viewed strictly from the time domain, this in-phase requirement does not exist. Similar to the bulk-optic-based direct space-to-time pulse shaper [14], the output temporal profile is simply given by

$$e_{\rm out}(t) = e_{\rm in}(t) * \left\{ \sum_{i=1}^{N} M{\rm split}_i \cdot \delta\left(t-(i-1)\tau\right) \cdot M{\rm combine}_i \right\} \tag{1}$$

where $e_{\rm in}(t)$ represents the input temporal profile, the M terms represent the effective "masking profile" of the splitter and combiner regions on a guide-by-guide basis, and τ and N are the delay increment per guide and number of guides in the waveguide array, respectively. The effective masking function of the splitter/combiner sections is given by the square root of the power split per guide shown in the previous section.

Of course, this simple time-domain argument relies on several assumptions: short input pulses, and minimal material dispersion being the most critical. For the device to fulfill its function as a repetition-rate multiplier, the input pulses must be shorter than the delay increment per guide within the waveguide array. Since, in practice for PLC-based devices, this delay is generally rather short (on the order of 1 to 2 ps), it is worth considering the role of material dispersion. The total average device path length is rather small ($\sim$14 cm) and is easily compensated with a small amount of DCF. While it is a simple matter to include an appropriate length of the DCF into the experimental setup to compensate the material dispersion of the average path length of the device, it is not possible to compensate the dispersion due to the difference in path lengths within the device. However, in our device, the maximum difference in path lengths is in the order of 5 mm. The dispersion arising from such small path length differences is important only for pulse durations below a few tens of femtoseconds.

V. COMPLETE PULSE REPETITION-RATE MULTIPLIER: EXPERIMENTAL RESULTS

The complete repetition-rate multiplier device has been fabricated in a standard NEL silica-on-silicon process following the design rules presented above. The delay increment per guide was selected to be 1.5625 ps in order to provide the flexibility of combining (with appropriate delay) multiple outputs to generate a continuous 640-GHz output train in a similar fashion, as was done in [7], although that functionality is not demonstrated here. Here, the focus is on the overall temporal window of the device. We will experimentally demonstrate that the character of the output pulse train is due to equally weighted contributions of both the splitter (Msplit) and combining (Mcombine) regions as shown in the previous section and indicated in (1).

Two different device designs will be presented: one where waveguide funnels are used in both the splitter and combiner regions, and the other where one waveguide funnel is used in conjunction with a conventional splitter/combiner. These two different device designs are employed to experimentally demonstrate the equal contributions of both the splitter (Msplit) and combiner (Mcombine) regions of the PLC on the output time-domain waveform. The two devices will be operated both in the "forward" and "backward" propagation directions in order to demonstrate the invariant nature of the output temporal profile.

A. Funnel/Funnel

Fig. 4 shows the output temporal profile, on a linear amplitude scale, of the device that utilizes the funnel waveguides on both the input and output side. Both "forward" [Fig. 4(a)] and "backward" propagations [Fig. 4(b)] show similar temporal character, as expected. The deviation from a perfectly flat output pulse train is due to a small guide-to-guide variation in the split ratio which is magnified, since the funnel is used

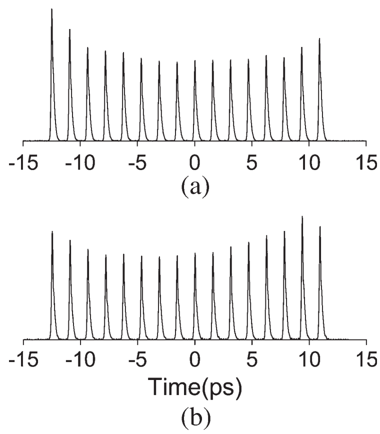


Fig. 4. Measured time-domain response of the funnel/funnel repetition-rate multiplier device both (a) "forward" and (b) "backward."

on both input and output ends of the device, experimental uncertainty in the optimum device coupling, and difficulty in precisely modeling the propagation in the funnel regions. Based on these measured time-domain profiles, it should be possible to optimize the splitter/combiner design and produce an even more uniform output pulse train.

The fact that the "forward" and "backward" propagation time-domain traces are not identical is due to the repeatability of fiber coupling in our home-made manually positioned fiber-coupling apparatus. Careful observation of the individual pulses making up the output pulse train shows that they are slightly asymmetric. This is due to a small cubic spectral phase (dispersion slope) that is not completely compensated by the DCF used to make the short pulse measurements. The time-domain measurements are performed for a fixed launch polarization along a principal state of polarization of the device in order to avoid a birefringence-based distortion. Measurements on both principal states of polarization show the time-domain responses that are identical to within the experimental repeatability of the fiber coupling to the devices.

B. Funnel/Conventional

Fig. 5 shows the output temporal profile, again on a linear scale, of the device that utilizes the funnel waveguides on one side (either input or output) and a conventional (AWG-like) splitter/combiner on the other side. The output temporal profile is essentially identical both in the "forward" [Fig. 5(a)] and "backward" [Fig. 5(b)] propagation directions. As explained previously, the $\sim$Gaussian temporal window is due to the power coupling of the conventional splitter/combiner. The symmetric role of $M\mathrm{split}_i$ and $M\mathrm{combine}_i$ from (1) is clearly shown in this data—regardless of the propagation direction, the same time-domain profile is measured.

C. Calculated Time-Domain Response

Using (1) and the measured power split as a function of guide number shown in Figs. 2 and 3, it is possible to obtain an expected time-domain response of the two device configurations. In order to simplify this calculation and presentation, the average loss of the two orthogonal launch polarization states shown in Figs. 2 and 3 is used to determine the mask profile of the splitter and combiner regions by calculating the transmission coefficient of each guide relative to the transmission of the center guides. Fig. 6 shows the time-domain response calculated in this way for both the funnel/funnel and funnel/conventional devices in reasonable agreement with the calculated time-domain responses shown previously.

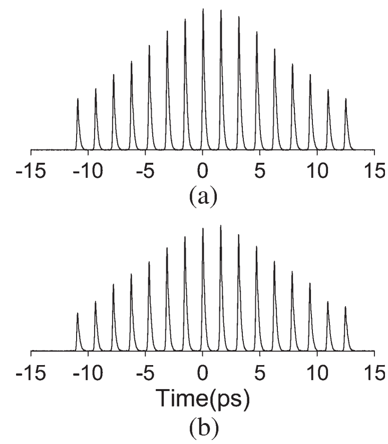


Fig. 5. Measured time-domain response of the funnel/conventional repetition-rate multiplier device both (a) "forward" and (b) "backward."

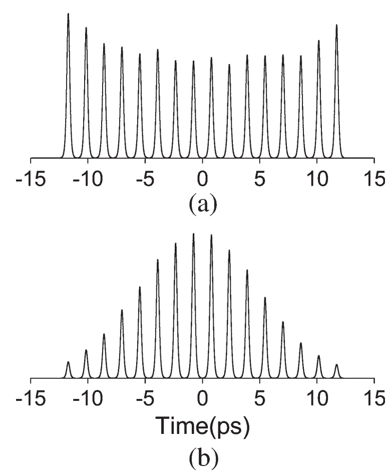


Fig. 6. Calculated time-domain response of the (a) funnel/funnel and (b) funnel/conventional repetition-rate multiplier devices.

VI. Conclusion

In summary, we have demonstrated that the repetition-rate multiplier devices generally based on time-domain design rules, and excitation-engineering specifically, are influenced equally by the design of both the splitter and combining regions. Both the calculated and measured time-domain responses are in reasonable agreement. The simple time-domain design rules developed here may impact future very high-speed repetition-rate multipliers and potential optical arbitrary waveform generation devices based on time-domain pulse manipulation.

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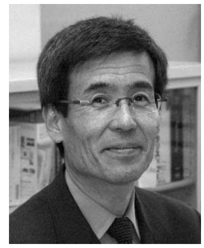

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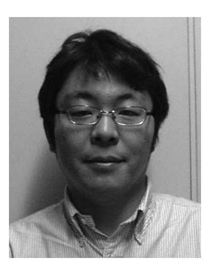

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