A high speed optical commutator switch for digital optical pulses

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ABSTRACT

A new optical commutator switch, capable of very high speed pulse generation and pulse multiplexing/demultiplexing, is proposed. It consists of an integrated optical Y-branch modulator and a "cul-de-sac" microstrip resonator. A possible compound digital optical modulator, using these optical commutators, is described. The results of measurements made on a cul-de-sac resonator, fabricated on an alumina substrate, and on optical Y-branch modulators, fabricated on z-cut lithium niobate substrates, are presented. For the resonator the unloaded quality factor was measured. For the optical Y-branch modulators the on/off ratios and percent guided powers were measured as functions of the applied voltage for several branch angles. The results indicate that optical commutators, of the type proposed, could be made.

1. INTRODUCTION

A novel optical commutator switch that is based on the integrated optical Y-branch modulator[1] and the "cul-de-sac" resonator[2] is proposed; by an optical commutator we mean an optical switch that alternately directs light from one input waveguide into one of two output waveguides. Our switch uses an optical Y-branch, fabricated in z-cut lithium niobate by the controlled in-diffusion of titanium, in conjunction with a microstrip resonator. The resonator has the shape of a "cul-de-sac" traffic sign, i.e., it has two substantially parallel legs which are unconnected at one end and connected via an open ring at the other end. The resonator is designed to be a half-wave (or an odd multiple of a half-wave) resonator. It is oriented so that its legs induce electric fields in the optical waveguides of the Y-branch and, via the electrooptic effect, direct light from the input waveguide into each of the output branches on alternate half-cycles of the centre frequency. Figure 1 is an illustration of an optical commutator; here we are assuming that the microwave is fed into the resonator by a matching quarter-wave transformer.

One application of these commutator switches is the generation, from a continuous wave input, of high speed optical pulses in the output branches. A second application is the directing of previously generated pulses into the two output waveguides on alternate half-cycles of the resonant frequency, e.g., as part of a synchronized demultiplexer; naturally, the reverse operation of combining previously generated pulses may be accomplished, e.g., as part of a synchronized multiplexer. Also, compound digital optical modulators are possible.

Figure 2 illustrates a compound digital optical modulator that uses optical commutators. Here narrow optical pulses are first generated and then distributed to a series of slower acting optical "killer" switches using two tiers of optical commutators, one operating at a centre frequency f and two operating at f/2. The killer switches selectively destroy the pulses. The surviving pulses are then

0-8194-0999-5/93/$4.00

multiplexed onto a single output waveguide using two more tiers of commutators in the reverse mode. The final pulse train has a repetition rate of 2f. Naturally, strict phase relationships must be maintained among all of the commutators. While the modulator illustrated in Figure 2 has only two tiers of commutators on both the input and the output, modulators having larger numbers of tiers should be possible.

In this paper we provide some of the results of our work on both the resonators, here fabricated on alumina substrates, and the optical Y-branch modulators, fabricated on z-cut lithium niobate substrates. These results indicate that optical commutators, of the type proposed, fabricated on z-cut lithium niobate substrates, could be made.

2. THE RESONATOR

The resonator is intended to act as a voltage transformer, i.e., developing a relatively large voltage between the ends of its legs while dissipating relatively little power. For our application, the voltage that develops between the ends of the legs should be 50 V for about 100 mW dissipated power at 15 GHz on a z-cut lithium niobate substrate.

While, as part of the optical commutator, the resonator would be fabricated on a z-cut lithium niobate substrate, in order to verify our concept, we fabricated resonators designed to operate at 7 GHz on alumina substrates. The model, as well as various other considerations, used in the design of the resonators is discussed in Reference 2. Also given in Reference 2 is the relationship between the output voltage V_o and the source voltage V_s (a lossless line between the source and the resonator is assumed); $V_o^2 \approx \{4\beta/(1+\beta)^2\} \times \{8Q_uZ_r/(\pi Z_s)\} \times V_s^2$, where β is the coupling coefficient between the source and the resonator, Z_r is the characteristic impedance of the microstrip constituting the ring portion of the resonator, Z_s is the characteristic impedance of the source, and Q_u is the unloaded quality factor of the resonator.

The resonators were fabricated on 0.89 mm thick alumina substrates. The microstrip constituting the resonator was made of gold, electroplated to a thickness of 6 μm. The ring portion of the resonator had a mean radius of 0.86 mm and a width of 0.14 mm, Z_r was 95 Ω. The legs were 1.3 mm long, 0.14 mm wide, and were separated by a 12 μm gap. The predicted value for Q_u was 180 for a centre frequency f_o of 7 GHz. The assumed values for Z_s and β were 50 Ω and 1, respectively. Using these values we predicted that 50 V would develop between the legs for an input power of 24 mW.

The measured normalized reflected power, for one such resonator, is shown in Figure 3. Since we used a reflection technique on a scalar network analyzer to take the measurements, the value of Q_u was not given by simply dividing the centre frequency by the 3 dB bandwidth but had to be adjusted to account for the different reflection coefficients at the various measurement points. The measured value for Q_u was 123 and for f_o was 7.12 GHz. Using these values we calculated that, to develop 50 V between the legs of this resonator at 7.12 GHz, an input power of 35 mW would be needed.

Using the same model, as that used above to design the resonators fabricated on the alumina substrates, we designed resonators for z-cut lithium niobate substrates that would operate at 15 GHz. We assumed that Z_s would be 50 Ω, that β would be 1, and that the microstrip constituting the resonator would be made of 6 μm thick gold. In this case the legs would be 0.35 mm long, 0.03 mm wide, and the gap between them would be 4 μm. The ring would have a mean radius of 0.79 mm and a width of 0.02 mm. Our predicted Q_u was 71 and Z_r was 62 Ω; giving 59 V between the ends of the legs for 100 mW input power. If we assume a 30% decrease in the Q_u of an actual resonator, as in the case above, this resonator should develop 49 V for 100 mW input power.

3. THE OPTICAL MODULATOR

A study of the optical Y-branch modulator was carried out to determine its usefulness in an optical commutator. Y-branches were both simulated and fabricated. Our study was used to determine the on/off ratios and percent guided powers, for various applied voltages and branch angles, for devices fabricated on z-cut lithium niobate.

In the simulations, the fundamental TM mode (λ_o = 0.6328 μm), having unit power, is assumed to be input to the Y-branch. The branch angles studied were 1.0°, 1.5°, and 2.0° and the electrodes were twice the length of the horn of the Y-branch, i.e., 0.46 mm, 0.30 mm, and 0.23 mm long, respectively; the horn is that portion of the Y-branch in which the two output waveguides begin to diverge from the input waveguide but are not yet separate. The electrodes run parallel from the narrow end of the horn, extending from the edges of the input waveguide, to the point at which the output waveguides begin to separate, they then run down the centres of the output waveguides for one more horn length. Simulations were performed for one, two, and three horn length electrodes for devices with both 1.5° and 2.0° branch angles, the two horn length electrodes gave the best results.

In the simulations the effective index method[3] (EIM) and the finite difference beam propagation method[4] (FDBPM) were used. First the EIM was used to reduce the refractive index distribution of the Y-branch from three dimensions to two dimensions by calculating an effective index for each point on the surface of the substrate, i.e., removing the depth dimension, leaving only a planar structure. The three dimensional refractive index profile, for the Y-branch, was calculated as described in Reference 3 assuming that titanium strips 4 μm wide (increasing to 8 μm in the horn) and 500 Å thick were in-diffused for 6 hr at 1050° C. The effect of applying a voltage to the electrodes was calculated using conformal mapping[5]. These voltages may be large enough to induce electric fields in the Y-branch that reduce the effective index, in specific locations, to values less than the refractive index of the undiffused substrate. To calculate effective indices for such locations we used the method described in Reference 6.

Optical Y-branch modulators were fabricated in lithium niobate. The fabrication parameters were those used in the simulations. The Y-branch pattern was formed by thermally evaporating a uniform film of titanium onto a z-cut lithium niobate substrate and then by patterning the titanium using photolithography and plasma-etching. The diffusion was done in wet oxygen to suppress lithium oxide out-diffusion[7]. A silicon dioxide layer was sputtered onto the surface to act as an optical buffer between the titanium in-diffused waveguides and the electrodes, preventing losses due to the optical waves interacting with the electrodes[8]. Then a 4000 Å thick layer of aluminum was thermally deposited and patterned into ordinary electrodes (not resonators) using photolithography and chemical wet-etching. The sample containing the modulators was then cut and the ends were polished to allow light to be coupled into the devices.

Polarized light, at $\lambda_o = 0.6328\ \mu m$, was launched into the TM-like mode of the devices from a polarization-preserving, single-mode, optical fibre. The outputs of the devices were focused, using a microscope objective, onto a pinhole in front of a detector. A slowly varying, 1 Hz, triangle wave was applied to the electrodes and the output was measured. In order to reduce the photorefractive effect, the power in the waveguides was kept to a few micro-watts. The on/off ratios from both the simulations and the measurements are shown in Figure 4. The percent guided powers for both the simulations and the measurements are shown in Figure 5. As can be seen, the agreement between the measurements and the simulations is quite good, showing close agreement in the predicted (theoretical) and measured (experimental) values as well as in the trends.

4. CONCLUSIONS

We have fabricated, on alumina substrates, resonators capable of developing relatively large voltages between the ends of their legs while dissipating small amounts of power. We predict that such resonators, fabricated on z-cut lithium niobate substrates, would be capable of developing 50 V for about 100 mW dissipated power at 15 GHz. The legs of such a resonator could be used as the electrodes of an integrated optical Y-branch modulator to form an optical commutator. We have simulated such Y-branch modulators, as well as having fabricated some on z-cut lithium niobate substrates. We have measured on/off ratios of 10, 10, and 11 dB and percent guided powers of 69%, 64%, and 39% for 50 V applied to the electrodes of modulators having 1.0°, 1.5°, and 2.0° branch angles, respectively. By combining the two structures it should be possible to fabricate optical commutators of the type proposed.

5. ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support of the Natural Sciences and Engineering Research Council of Canada.

6. REFERENCES

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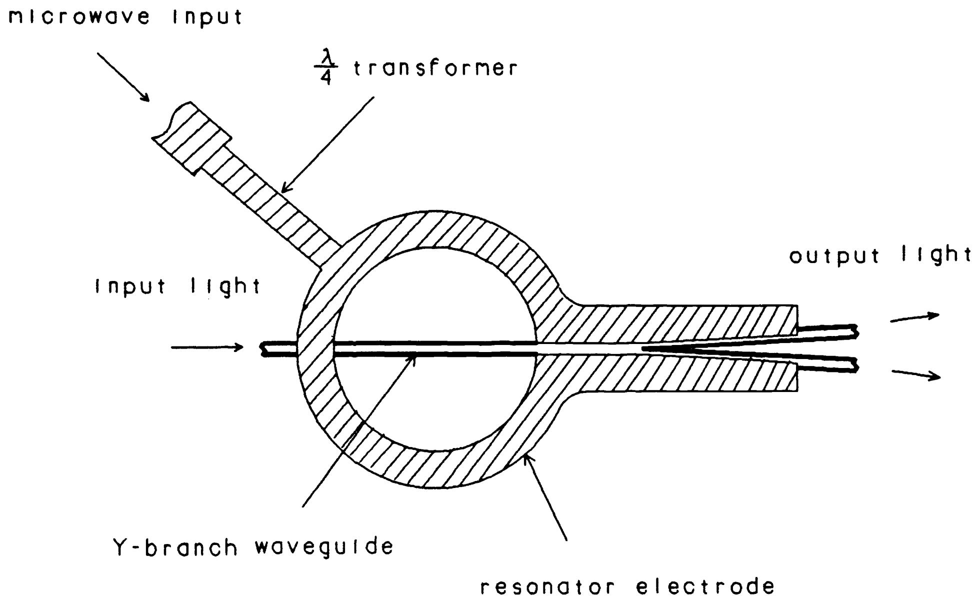

Figure 1. An integrated optical commutator.

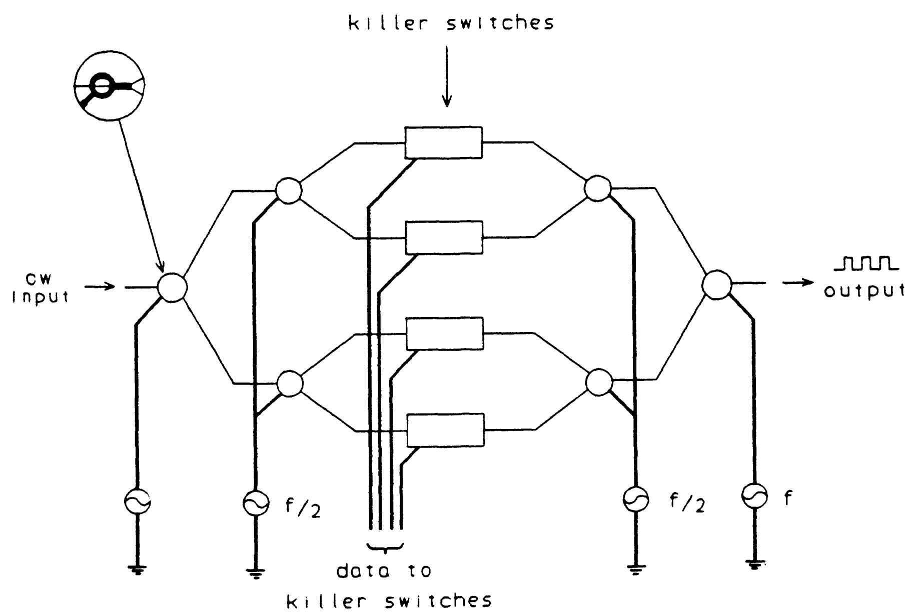

Figure 2. A compound digital optical modulator.

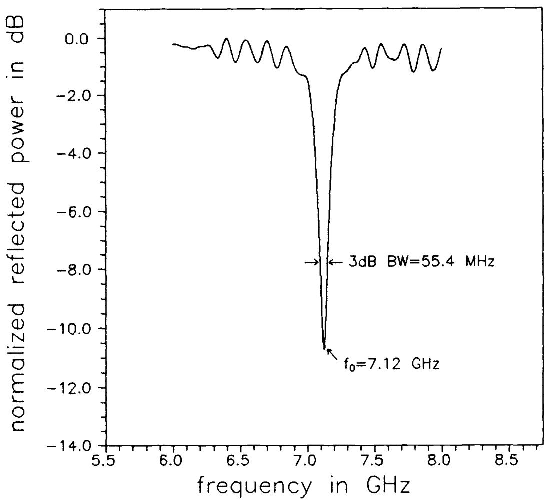

Figure 3. The normalized reflected power vs. frequency for a cul-de-sac resonator.

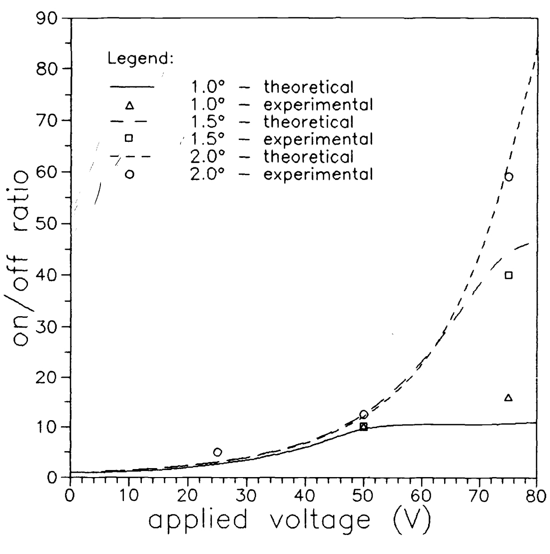

Figure 4. The on/off ratios vs. applied voltage for the optical Y-branch modulators.

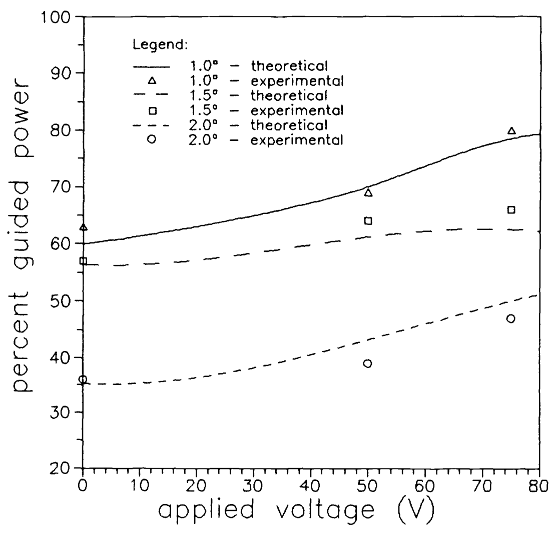

Figure 5. The percent guided powers vs. applied voltage for the optical Y-branch modulators.