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6. $\tilde{n}_2 = (1/n_{\mathrm{eff}})\iint n(y)n_2(y)|E|^4 dxdy/\iint|E|^2 dxdy$, where $n(y)$ is the distribution of the refractive index that represents the guide structure, n_2 is the nonlinear coefficient of the guide, and n_{eff} and E, respectively, are the effective index and the electric field of a guided wave that is written as $U(x, y, z) = A(z)E(x, y)\exp[j(2\pi n_{\mathrm{eff}}z/\lambda + \phi(z)]$. If the guided wave is weakly perturbed by detuning and nonlinearity, $\tilde{n}_2$ is the constant that is provided by that in the linear case.
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Ion-exchanged Mach–Zehnder interferometers in glass

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Received 29 May 1991.
0003-6935/92/183381-03$05.00/0.

Ion-exchanged Mach–Zehnder interferometers are produced in glass. The effect of fabrication parameters on their optical response in relation to their constituent components is investigated.

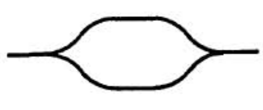
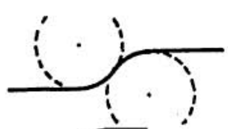
Mach–Zehnder interferometers have important applications in integrated optical circuits in glass.[1,2] A Mach–Zehnder interferometer is composed of different waveguide components: Y branches, S shapes, and straight channel waveguides. Below we refer to these waveguides as the building components of the interferometers.

The overall optical response of a Mach–Zehnder interferometer depends on the optical characteristics of its components. In turn, the optical properties of these components are governed by their fabrication parameters. Hence an accurate knowledge of the behavior of these components is essential for making an interferometer with a desired optical specification. Here we produce Mach–Zehnder interferometers by an ion exchange in a glass substrate. Their components are also individually fabricated. The transmission properties of the interferometers and their components are thoroughly studied.

A potassium ion-exchange process in a Corning 0211 glass substrate was employed to produce the interferometers and the components. Ion exchange was carried out through the openings in an aluminum mask. Table I summarizes the fabrication parameters. For transmission spectra measurements, light from a tungsten-halogen lamp was coupled into the interferometers and components, and the output was measured by a spectrometer. A He–Ne (0.6328-μm) laser and a Nd:YAG (1.06-μm) laser were used to determine the number of modes and losses.

Figures 1 and 2 depict typical examples of transmission spectra of some of the fabricated interferometers and components. A study of these spectra reveals that: 1, cutoff wavelengths (which are defined as the wavelengths that transmission decreases by 3 dB) for the interferometers and

Table I. Fabrication Parameters and Characterization Results of Interferometers and Components made by Potassium Ion Exchange[a]

Sample Number		Structure	Mask Width (μm)	Ion-Exchange Time (h)	Bend Radii (mm)	Cutoff Wavelength (μm)
C1	Channel		10	5	—	1.68
MZ1	Mach–Zehnder		10	5	—	1.16
MZ2	Mach–Zehnder		10	2½	30	0.97
MZ3	Mach–Zehnder		10	4	30	1.12
MZ4	Mach–Zehnder		10	6	30	1.37
S1	S shape		10	5	60	1.41
S2	S shape		10	5	40	1.31
S3	S shape		10	5	30	1.22
S4	S shape		10	5	20	1.10
Y1	Y branch		10	5	30	1.21
Y2	Y branch	 0.5°	5	2	—	1.47
Y3	Y branch	 2.5°	5	2	—	1.47

[a]Ion-exchange temperature is 400°C. Pure potassium nitrate baths are used.

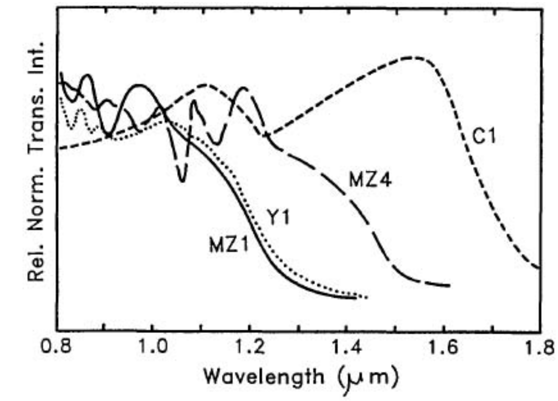


Fig. 1. Transmission spectra of two Mach–Zehnder interferometers, a Y branch, and a straight waveguide. See Table I for fabrication parameters. Y1 is from one of the output ports of the Y branch. Rel. Norm. Trans. Int., the relative normalized transmission intensity.

the components with curved waveguides are lower than those of straight waveguides; and 2, oscillations in the shorter wavelengths in the spectra of the interferometers exist.

Table I summarizes the cutoff wavelengths in the interferometers and the components. The decrease in the cutoff wavelength is mainly due to long wavelength losses in the S-shaped waveguides. To investigate this matter further, propagation losses in the straight and S-shaped waveguides were measured, and the excess losses (which are the propagation losses in the S-shaped waveguides minus the propagation losses in the straight waveguides) were determined at 1.06 μm. Propagation losses in a straight waveguide were ~0.2 dB/cm. The results, which are given in Fig. 2, show that the excess losses in the S-shaped waveguides increase drastically by reducing the bend radii. At this wavelength the input (straight) waveguides have two modes. For a better understanding of the behavior of these components, the evolution of the modes along the components was studied. Submicrometer-etched gratings[3] were made in the input and output (both straight) waveguides as well as in the curved waveguides. These gratings diffract (in the air) some of the light at each guided mode, which can be observed easily with an infrared camera (for 1.06 μm) or on a screen (for 0.6328 μm). Lights at 0.6328 μm and 1.06 μm were coupled into the components by a microscope objective to ensure excitation of all the modes. The diffraction of the lights by the grating in the input waveguide indicated that the straight waveguide had two modes at both 0.6328 μm and 1.06 μm (the higher-order mode is weakly guided at 1.06 μm). In samples S1, S2, and S3, both modes were guided in the curved part of the sample and both exited from the output waveguide. However, in sample S4, the higher-order mode disappeared in the curved part and only one mode (fundamental) was observed at the end. In another set of experiments, only the fundamental mode of the input waveguides was excited by using an optical fiber. It was observed that light was guided throughout the component by the fundamental mode and there was no coupling of light to the higher-order modes.

Oscillations of ~100-nm period are evident in the spectra of the interferometers, along with the smaller, less identifiable perturbations. It is worth emphasizing that the interferometers were designed to be balanced, i.e., with equal optical paths in the two arms and exact 3-dB splitting in the Y branches. Therefore their transmission should be wavelength independent. However, if the interferometer is not operated in the single-mode regime, the balance may be lost. It has been observed before that oscillations appear in the splitting ratios of Y branches when the wavelength reaches the cutoff of high-order modes.[4] This is due to modal interference at the junction, which leads to unequal excitation of the two arms. Another possible cause of the oscillations may be a slight imbalance of the optical pathlengths. A path difference of a few tens of nanometers can result in such oscillations. However, the oscillations seem to stop at wavelengths longer than those of the first spectrum peak, which indicates that the interferometer is operating in an equivalent-to-single mode regime beyond that point.

To study further the effect of Y branch, we made two supplementary samples Y2 and Y3 (see Table I). To isolate the effect of the Y branch, S-shaped waveguides were not utilized. To ensure a single-mode operation along these devices a smaller mask width (5 μm) and a shorter ion-exchange time were employed. Different branching angles (0.5° and 2.5° respectively) were used. Figure 3 compares transmission spectra of the Y branches. The oscillations are due to modal interference in the branching area. In the single-mode regime (equivalent single-mode regime for Y1) the input waveguide of Y1 has two modes while those of Y2 and Y3 have only one mode. This results in an unequal

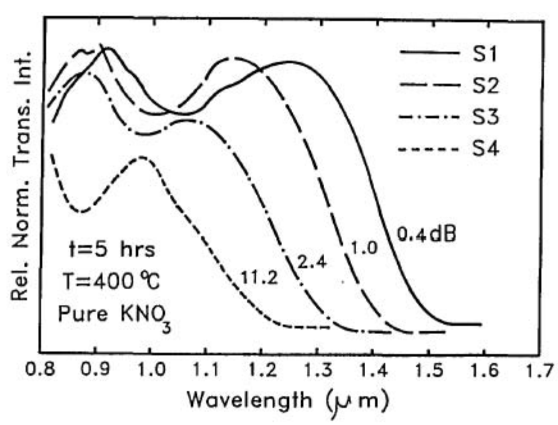


Fig. 2. Transmission spectra of S-shaped waveguides with different curvatures. See Table I for fabrication parameters. The number beside each curve is the excess loss of the S-shaped waveguide with respect to a similar channel waveguide at 1.06 μm.

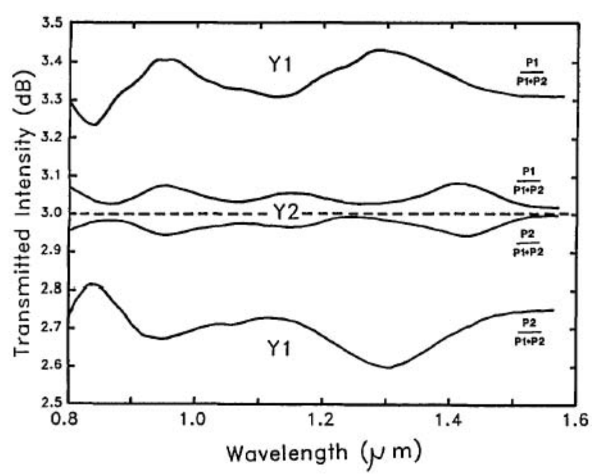


Fig. 3. Transmission spectra of three Y-branch waveguides without S-shaped waveguides. See Table I for fabrication parameters. P1 and P2 are power outputs from the two branches. The deviation from 3-dB splitting ratio for Y3 is similar to Y2.

excitation of the modes in the branching point and leads to a larger deviation in the splitting ratio. Deviation should decrease if only the fundamental mode in the input waveguide is excited, for example, by using a tapered waveguide.

In summary, we have identified and studied the different contributions of a Mach–Zehnder integrated optical interferometer in glass to wavelength response. It was shown that the oscillations in the spectral response of these interferometers are due to the Y branches used in their construction. The concept of an equivalent single-mode regime wavelength range was introduced to describe the differences in the modal cutoff behavior of these devices relative to the straight channels from which they are constructed.

This work was funded in part by a strategic research grant (STR0100950) from the National Sciences and Engineering Research Council of Canada (NSERC).

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Spectral modulation of two coherently separated femtosecond laser pulses

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Received 1 August 1991.
0003-6935/92/183383-02$05.00/0.

A train of 150-fs 76-MHz pulses is directed into a Michelson interferometer with a path difference larger than the pulse spatial length. A modulated spectrum with a modulation frequency that increases with the path difference is observed. The consequence is discussed.

We report an experiment in which the spectra of two coherently separated femtosecond pulses are measured. Modulation of the spectra is observed for separations of the two pulses larger than the pulses' spatial width. This experiment is similar to those performed by Delisle and co-workers,[1–7] in which incoherent white light was directed upon a Michelson interferometer and spectral modulation of the combination of the waves from the two arms was observed at path differences that were longer than the coherence length of the light. Despite the short coherence length of the white light, it was thought that the spectral modulation would be due to the constructive or the destructive interference of the infinite number of different monochromatic components of the cw light source for a fixed path difference. In principle, the same results are obtained if the intensity of the white-light source is reduced to one photon going through the interferometer at a time. Furthermore, a train of femtosecond pulses from a laser should be equivalent to a random distribution of photons, except for the order of the arrival of the pulses and also the number of photons per pulse. However, an interference experiment that measures pulses that are separated in space yet still have a coherent superposition of monochromatic components may seem surprising. We report that the spectrum of a train of short pulses is indeed modulated after passing through an interferometer with a path difference larger than the pulses' length. These results indicate that the femtosecond pulses are a Fourier superposition of monochromatic components, in agreement with theory.

A train of 150-fs 76-MHz pulses from a sync-pumped cw mode-locked dye laser (Quantronix 4500) was directed upon a Michelson interferometer. The pulse temporal width was measured with an autocorrelator. The pulses from the two arms were then recombined and sent into a spectrometer

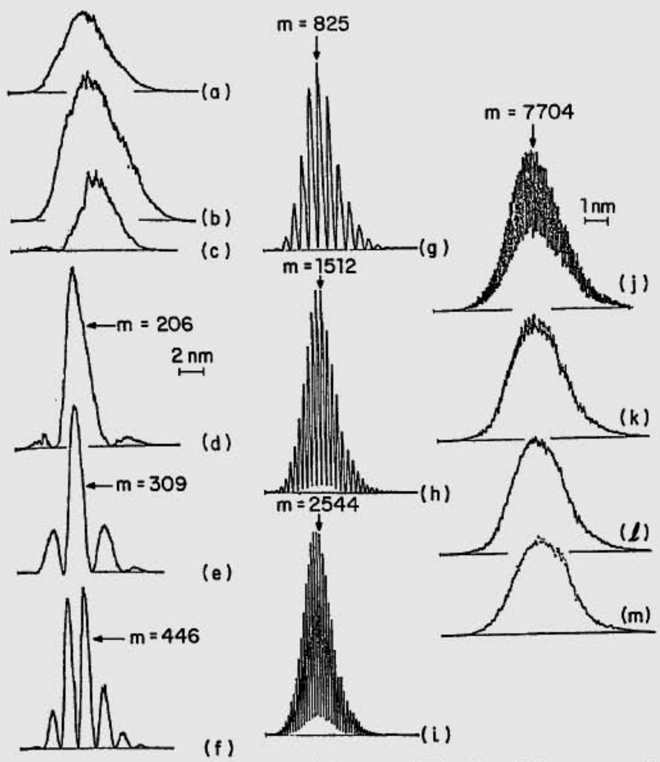

Fig. 1. Spectral distribution of the recombination of femtosecond pulses that come from a Michelson interferometer. The vertical scale is arbitrary. The integer m indicates the value at which the condition of constructive interference [Eq. (1)] is satisfied for that particular peak. Successive peaks will increase or decrease by increments of one from m. For the horizontal axes, all the spectra start at 577 nm. The scale in (a)–(i) is 2 nm, and the scale changes to 1 nm in (j)–(m). (a) One arm of the interferometer is blocked. (b)–(m) Show the respective path differences (PD's) between the two arms: (b) ≈ 0, (c) 80 μm, (d) 120 μm, (e) 180 μm, (f) 260 μm, (g) 480 μm, (h) 880 μm, (i) 1.48 mm, (j) 4.48 mm, (k) 10.48 mm, (l) 20.48 mm, (m) 40.48 mm.