INVITED PAPER

Optical intensity modulator using inverted slot line at 60 GHz

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The inverted slot line (ISL) structure which has been proposed for millimetre wave LiNbO₃ optical modulator is found to be very simple in structure, and is also capable of easily achieving a perfect velocity matching between carrier and modulating waves. This paper describes the analysis of the ISL based on the spectral domain approach and the practical development of a Mach–Zehnder Ti-diffused LiNbO₃ optical intensity modulator using the ISL at 60 GHz. To launch millimetre waves into the ISL structure two types of transitions have been developed successfully. In one type, a balun which is made from a semi-rigid coaxial cable is used to feed millimetre waves into the ISL. In another type, a non-radiative dielectric (NRD) waveguide which can provide the total integration of the modulator with millimetre wave integrated circuits is used to excite the ISL structure ensuring minimum transition losses. A modulator response of 0.17 W⁻¹ could be obtained at 60 GHz using a Mach–Zehnder interferometer with a rather poor extinction ratio at an optical wavelength of 0.633 µm.

1. Introduction
Research on millimetre wave optical modulators has become extremely popular due to the increasing demand for fibre optic/millimetre wave radio links for future personal communication applications. The efficiency of optical modulation is limited by the velocity mismatch between optical waves and millimetre waves. Various techniques for achieving velocity matching have been proposed so far [1, 2].

An inverted slot line (ISL) structure which has been proposed in [3] is found to be very useful for realizing a millimetre wave LiNbO₃ optical modulator having a high efficiency of modulation. The ISL is a conventional slot line which is placed upside down over a ground plane with a small spacing in between. The structure is simple and can be fabricated easily. Since the electric field in the slot line is predominantly parallel to the ground plane, guided millimetre waves approach the below-cut-off state in the space between the electrode and the ground plane and hence the phase velocity increases as the spacing decreases.
In this paper the analysis of the ISL based on the spectral domain approach is described. The uniaxial property of the LiNbO₃ substrate is taken into account fully. The perfect velocity matching between optical and millimetre waves and the characterization of the ISL in terms of effective refractive index are demonstrated theoretically.

The practical development of a Mach–Zehnder Ti-diffused LiNbO₃ optical intensity modulator using the ISL at 60 GHz is described. Since the electric field in the slot line is horizontally polarized, a Y-cut LiNbO₃ substrate has been used. From the modulated optical waveform the modulator response of 0.17 W⁻¹ could be estimated at 60 GHz using a Mach–Zehnder interferometer with a rather poor extinction ratio at an optical wavelength of 0.633 µm. This is a promising result at millimetre wave frequencies and it is expected that improvement in the extinction ratio will further enhance the modulator performance significantly.

2. Formulation by spectral domain approach

The ISL structure is shown in Fig. 1, together with the co-ordinate system in which the x and y axes are in the transverse plane and the z axis is in the longitudinal direction. The ISL is a conventional slot line which is placed upside down over the ground plane with a small but proper spacing. The thickness of the LiNbO₃ substrate is denoted by \( d \), the width of the slot by \( 2w \), and the spacing between the electrode and the ground plane by \( s \).

At first, we must note that LiNbO₃ material is uniaxial in crystal structure. In order to take into account such a particular property we introduce an effective relative permittivity \( \epsilon_r \) and an effective substrate thickness \( d' \) for simplicity by the expressions

\[
\epsilon_r = (\epsilon_x \epsilon_y)^{1/2} \tag{1}
\]

\[
d' = \left( \frac{\epsilon_x}{\epsilon_y} \right)^{1/2} d \tag{2}
\]

where \( \epsilon_x \) and \( \epsilon_y \) are relative permittivities of the substrate in the x and y directions, respectively and for the Y-cut LiNbO₃ substrate, we have \( \epsilon_x = 28 \) and \( \epsilon_y = 43 \). We can replace the original substrate with the isotropic one by means of the above equivalent relations which have been proved to be valid within the static field approximation [4].

The fields in the ISL are hybrid, and can be found if we assume the y components of the electric and magnetic fields as follows:

In the substrate \((0 < y < d')\),

\[ \text{Figure 1} \quad \text{The structure of the ISL.} \]