Optical imaging of multimode interference patterns with a resolution below the diffraction limit

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OPTICAL IMAGING OF MULTIMODE INTERFERENCE PATTERNS WITH A RESOLUTION BELOW THE DIFFRACTION LIMIT

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Abstract

For the first time the optical interference pattern in multimode interference couplers operating at 1485 nm is made visible using an optical microscope. This is done by imaging the green light (519 and 545 nm) which is generated by upconversion at high pumping power levels in waveguides with a high erbium concentration. As the intensity of the green light is roughly proportional to the fourth power of the pump signal intensity it thus becomes possible to image the 1485 nm intensity distribution with a resolution limited by the diffraction limit for 519 and 545 nm light.

Introduction

Accurate methods for measuring two-dimensional intensity patterns in integrated optical devices are not available at present. Techniques which image the light scattered at inhomogeneities in the waveguide layer suffer from the large local inhomogeneity of the scattering sources. Another method is positioning identical devices at different distances relative to a cleaved endface. This method only provides us with one-dimensional intensity scans at different positions in the devices, provided that the excitation conditions can be reproduced. In this paper we present a method of imaging the field patterns in integrated optical devices using two-step cooperative upconversion in erbium ions incorporated in the waveguides. Cooperative upconversion is a process in which two excited Er^{3+} ions exchange energy, promoting one of them to a higher energy level [1]. Two sequential upconversion processes lead to emission of green (519 and 545 nm) light. As the process depends on the concentration of excited Er^{3+} ions, which in turn depends on the intensity of the field distribution, the emission of green light is a (roughly fourth-power) replica of the intensity distribution in the waveguide.

Upconversion mechanism

Figure 1 shows the energy level diagram of Er^{3+}, and a schematic of how cooperative upconversion proceeds. The various energy levels of the Er^{3+} ion are numbered 0-6. Figure 1a illustrates the first-order process between two Er^{3+} ions in the first excited state, whereby one of them transfers its energy to the other, promoting the latter to the 3rd excited state. This process depends quadratically on the concentration of Er^{3+} in the first excited state, as two ions are involved. The ions in the third excited state decay rapidly and non-radiatively to the second excited state. Because the lifetime of level 2 is relatively long (0.25 ms) a significant population in the second excited state is built up.

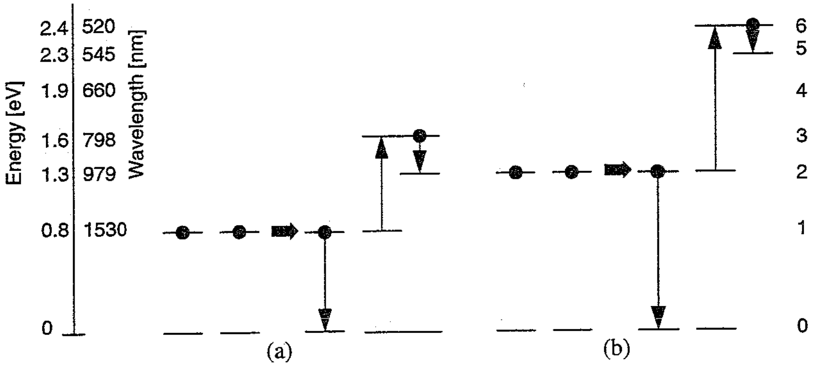


Figure 1. Energy level diagram of Er^{3+}, showing cooperative upconversion.

Subsequently, a second upconversion process can take place (Fig. 1b), in which two ions in the second excited state interact in a similar fashion, thereby populating the 6th excited state. Radiative decay from this state to the ground state causes emission at 519 nm. In addition, non-radiative decay can occur to the 5th excited state; radiative decay of this state to the ground state causes emission at 545 nm. The emission of this visible green light is roughly proportional to the 4th power of the concentration of Er^{3+} in the first excited state, as two subsequent upconversion steps are involved. It thus becomes possible to directly image the intensity distribution of 1.48 μm pump light by monitoring the green emission. The measurement resolution is then limited by the diffraction limit for 519 and 545 nm light.

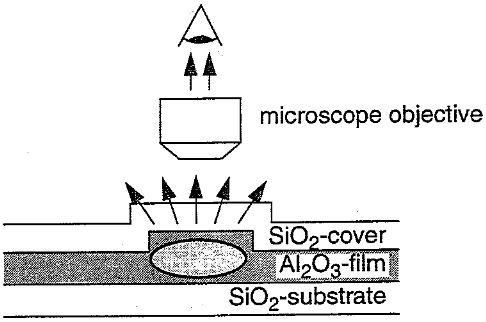


Figure 2. Principle of the measurement setup.

Measurement principle

Figure 2 shows the measurement setup, where a simple microscope objective placed above the waveguide is used for imaging the intensity distribution of green light as the 1485 nm light is guided through the waveguide. Accurate measurements can be made by digitizing the output on a CCD camera. The fourth power dependence between the green light and the IR light is favourable for obtaining high measurement accuracy. The short wavelength of the upconverted light makes it possible to measure with a resolution considerably below the diffraction limit for the infrared light, which allows for high accuracy imaging with medium quality objectives.

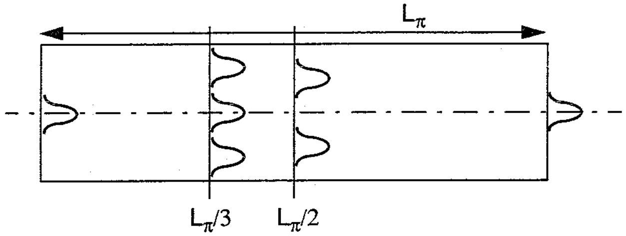
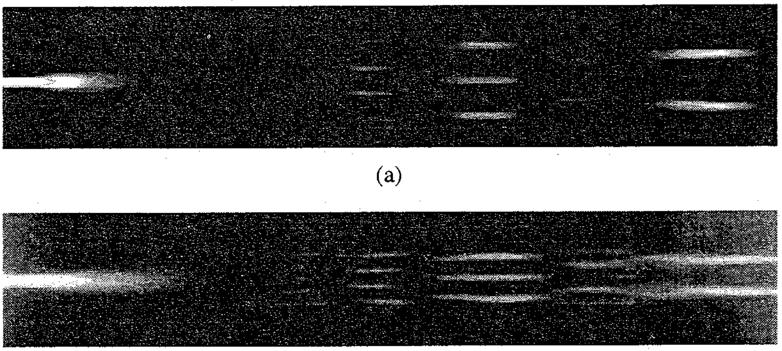


Figure 3. Schematic diagram of the self-imaging principle in a MMI-coupler.

MMI-coupler simulation

A property of multimode waveguides is self-imaging, which means that an input field is reproduced in single or multiple images at periodic intervals in the MMI-section as shown in Fig. 3. The principle can be explained as follows. An applied input field is decomposed into all guided modes of the MMI-section, each of them propagating with a different propagation constant. After a certain length L_π all modes appear to interfere constructively, resulting in an image of the input field. At distances L_π/N an N-fold image of the input field is obtained, so this type of MMI-coupler can be used as power splitter. The principle of MMI-couplers are discussed in detail by Soldano [2].


(a)

(b)

Figure 4. Multimode interference pattern: a) BPM-simulation, and b) a microscope image, visible as green light.

Figure 4a shows the result of a simulation performed with the Beam Propagation Method (BPM) using a 21 μm wide MMI-section centre-fed by a 2 μm wide input waveguide. The light coming out of the input waveguide is seen to diverge in the MMI-section and to be reflected by the sidewalls. The reflections cause the interference patterns which produce at certain distances the single and multiple images typical for MMI devices.

Experiment

An MMI-coupler was fabricated in an aluminum oxide ridge waveguide structure [3], implanted with erbium [4] to a peak concentration of 1.3 at.%. The device consists of a 2.0 μm wide input waveguide, centre-fed to a 21.0 μm broad MMI-section. Light from a 1485 nm high power laser was coupled into the input waveguide using a fiber taper. The power in the waveguide was 4 mW. Figure 4b shows the microscope image of the multimode interference pattern, right after the transition from the input waveguide to the MMI-section. This image appears as green light due to a two-step cooperative upconversion process as explained above. As can be seen the measured intensity profile agrees very well with the calculated profile in Fig. 4a.

Conclusion

Cooperative upconversion of Er ions pumped at 1485 nm can be used to image intensity distributions in waveguides with a high accuracy and resolution below the diffraction limit. This is demonstrated with a MMI-coupler fabricated in aluminum oxide ridge waveguide structure implanted with erbium. The calculated intensity profiles agree very well with the measured data. This method offers an unique opportunity for accurate measurements of lateral field patterns.

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