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We report the realization and characterization of a tunable, two-dimensional Talbot array illuminator for mid-infrared (MIR) wavelengths. A phase array, prepared by deposing tin-doped indium oxide electrodes on a square-lattice-geometry poled $LiNbO_3$ sample, is illuminated by a difference-frequency generator emitting at 3 μm. Then, combining the electro-optic with the Talbot effect allows generation of a variety of light patterns under different values of distance and external electric field. Several potential applications with great relevance to the MIR spectral region are discussed. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3109794]

Shaping of laser beams, either in amplitude or in phase, represents a topic of growing interest in different research fields such as optical trapping, optical interconnection, tunable-mask lithography, adaptive optics, and light transmission through strongly scattering or opaque materials.[1] Wave-front engineering has already produced plenty of applications and commercial devices in the visible and near-infrared (NIR) parts of the spectrum, where fabrication technologies are well established. Among the various light-structuring tools, a wide exertion is found by Talbot array illuminators (TAIs).[2,3] These are diffractive phase elements, operating in the Fresnel regime, that transform a plane wave into an array of bright spots. For that reason, they are earning great consideration for use in optical computing and multiple imaging.[4,5] However, very few examples of wavefront-tailoring systems have been reported so far in the mid-infrared (MIR) spectral region.[6] The latter is of enormous scientific and technological interest because most of simple molecules have *fingerprint* absorptions in this range. In addition, the atmospheric transmission window between 3 and 5 μm enables free-space optical communications, thermal imaging, and development of countermeasures for homeland security.[7] Actually, recent advances in MIR optical materials have led to the development of new effective coherent sources and components, thus vastly increasing the number of applications and triggering, at the same time, more and more challenging experiments.[8] Some significant examples are correction or manipulation of wavefronts propagating through turbulent or scattering media,[9] implementation of photonic circuits for MIR integrated optoelectronics,[10,11] and realization of tunable liquid microlenses actuated by IR light-responsive hydrogel.[12]

In this letter, we demonstrate a tunable, two-dimensional (2D) TAI working in the MIR wavelength region. It is based on a square-lattice phase array (PA), which is dynamically imprinted in a domain-engineered *Z*-cut lithium niobate crystal.[13,14] A difference-frequency-generation (DFG) source emitting at 3 μm is used to test the performance of such component. A further evolution of this device, consisting of a patterned PA, where the phase of individual array elements is addressed, may turn out to be extremely promising for coherent beam combining to realize more powerful MIR sources.[15] In such configuration, by properly adjusting and actively controlling the relative phase between adjacent elements in the array, the required degree of mutual coherence among *N* input IR beams would be achieved, thus generating an output with enhanced power (by a factor of *N*) and preserved spectral linewidth. This perspective sounds particularly attractive for the novel quantum cascade lasers, provided that substrates and electrodes with suitable optical transparency are available.

The experimental apparatus is shown in Fig. 1. The DFG source, sketched in the upper frame, was described in detail

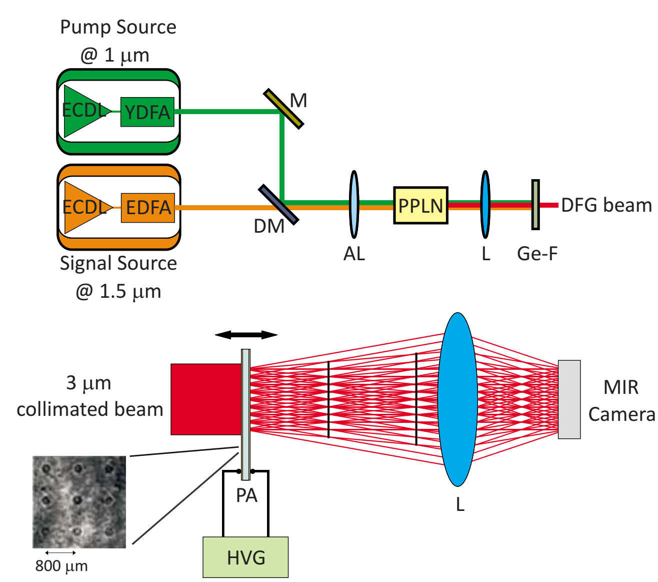

FIG. 1. (Color online) A 3 μm coherent radiation beam is produced by a DFG process. Then, a TAI is realized by propagation through a tunable, 2D phase grating. The latter consists of a domain-engineered *Z*-cut lithium niobate crystal covered with a couple of ITO electrodes. The actual domain structure in a selected region of the PA sample is also shown. The following legend holds: ECDL=external-cavity diode laser, E(Y)DFA =erbium(ytterbium)-doped fiber amplifier, M=mirror, DM=dichroic mirror, AL=achromatic lens, L=lens, Ge–F=germanium filter, and HVG =high-voltage generator.

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in a previous paper.[16] The signal (pump) beam comes from an external-cavity diode laser emitting from 1520 to 1570 nm (1030–1070 nm) and is amplified by an Er(Yb)-doped fiber amplifier up to 8 W (700 mW). Then, the two laser beams are superimposed to each other and focused into a periodically poled $LiNbO_3$ crystal, where the DFG process takes place. In this way, coherent radiation is produced in the 2.9–3.5 μm range with a maximum power of 3 mW. Finally, the emerging idler beam is filtered from the unconverted NIR light by a germanium window. A variety of cylindrical transverse mode patterns can be obtained for the idler radiation, depending on the specific matching conditions.[17] In the current investigation, a TEM_{00} mode is generated; then, a calcium fluoride lens is used to produce a well-collimated beam, which then propagates through the PA device.

This consists of a 2D square lattice (800 μm size) of inverted ferroelectric domains fabricated in a *Z*-cut $LiNbO_3$ substrate, including two transparent electrodes on the opposite *Z* faces. The poled sample was prepared by standard electric field poling at room temperature, as described in previous works.[13] Afterwards, transparent indium tin oxide (ITO) was deposited using a planar magnetron sputtering equipment with a dc-pulsed technique, from a 99.99% pure ceramic ITO target (91 mol % ln_2O_3–9 mol % SnO_2 composition). The $LiNbO_3$ substrate was placed on the substrate holder and the deposition chamber was pumped down to a base pressure of 3×10^{-6} mbar at 100 °C substrate temperature. The deposition (8 min duration) was performed at 50 W dc-pulsed power, with 70 kHz frequency and 30% duty cycle, at a pressure of 2.5×10^{-2} mbar with a constant Ar flux of 40 SCCM (SCCM denotes standard cubic centimeter per minute at STP). After this processing, a thickness of 150 nm (by conventional stylus profilometer) and a sheet resistance of 60 Ω/sq. (by four-point probe measurement) were measured for the deposed film. Indeed, the above deposition procedure represents a good compromise between electrical conductivity and overall optical transparency at 3 μm (around 35%). In particular, the dc-pulsed technique exhibits a substantially higher transmittance with respect to the radio-frequency (rf) sputtering procedure used to realize ITO-on-$LiNbO_3$ samples in a previous work.[13] This is shown in Fig. 2 where the continuous (dotted) transmission curve versus wavelength, as recorded by a Fourier transform infrared (FTIR) spectrometer, corresponds to a 400-nm-thick ITO film deposed on a $LiNbO_3$ substrate by the dc-pulsed (rf) technique. Such value is confirmed by that measured directly using the DFG source at a given wavelength for three different thickness values (see Fig. 3).

The tunable TAI is obtained by creating, through the electro-optic effect, a 2D phase grating in the PA sample. For this purpose, an external voltage *V* is applied along the *z* axis of the device via the ITO electrodes. This causes a phase change across the hexagonal domain walls given by[13]

$$\Delta\phi = (4\pi V/\lambda)[(n_0-1)d_{33}-(1/2)r_{13}n_0^3], \quad (1)$$

where λ is the wavelength of the DFG beam, n_0 is the $LiNbO_3$ ordinary refractive index, and $r_{13}=10$ pm/V and $d_{33}=7$ pm/V are the appropriate elements of the electro-optic and piezoelectric tensor, respectively. Finally, the 3 μm diffracted beam emerging from the PA is projected by an objective lens onto a LN_2-cooled, indium antimonide

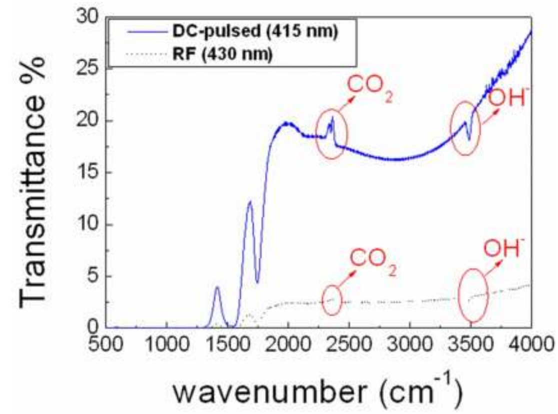

FIG. 2. (Color online) Transmittance curves recorded by FTIR spectroscopy for a 400-nm-thick ITO film deposed on a $LiNbO_3$ substrate by the dc-pulsed and rf technique, respectively. Deposition settings for the former are the same as those given in the text except for duration (20 min in this case), while for the latter technique the list of optimized parameters is power =100 W, temperature=300 °C, Ar flux=20 SCCM, pressure =0.025 mbar, and duration=20 min. Absorption features due to atmospheric CO_2 and OH^- ions present in $LiNbO_3$ are also visible.

(InSb) camera consisting of an array of 320×256 square pixels (30 μm size). The actual domain structure of the sample was visualized by focusing the PA sample, with an applied voltage, on the camera array plane (see Fig. 1). From this picture, the magnification ratio (1.5×) of the imaging arrangement was accurately determined for the subsequent acquisitions. In the case of diffraction by a periodic phase structure, an amplitude modulation along the propagating direction is generated at the planes defined by $z=[N+(P/Q)]Z_T$, where *N*, *P*, and *Q* are not negative integers ($P<Q$), and Z_T is the well-known Talbot distance.[2] For a square lattice with size *d*, this is equal to $Z_T=2d^2/\lambda$. For the maximum applied voltage $V=6$ kV, which amounts to a phase change $\Delta\varphi_{max}=(2/5)\pi$, a selection of intensity distributions, each corresponding to a different *z* value, is recorded by translating the PA device (see Fig. 4). Vice versa, at a given observation plane, the intensity pattern can be tuned by varying $\Delta\varphi$ via the applied voltage. However, in order to obtain an appreciably different intensity distribution, the change in $\Delta\varphi$ must be greater than $\pi/4$, whereas for

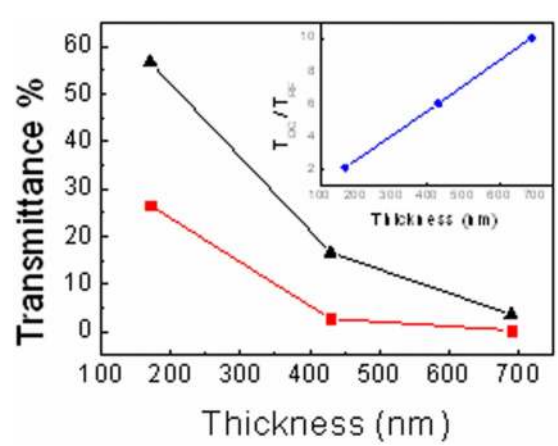

FIG. 3. (Color online) Optical transmission values for three different ITO thickness values as measured by the DFG source emitting at 3.07 μm. Triangles (squares) data points correspond to the dc-pulsed (rf) case; the ratio between them exhibits a linear behavior as a function of thickness (see inset).

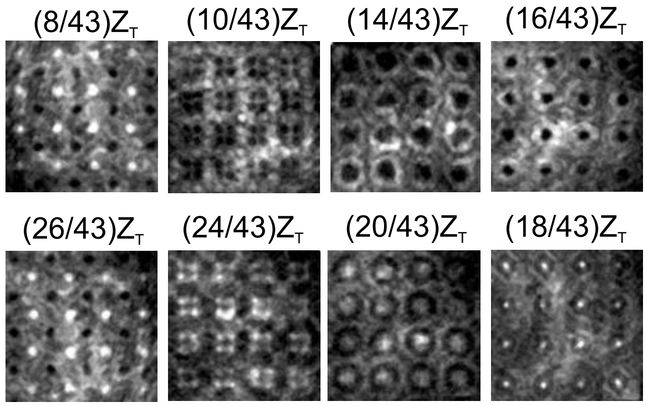

FIG. 4. Intensity distribution patterns generated at different fractions of the Talbot distance (Z_T=43 cm) for a fixed applied voltage V=6 kV. Each frame in the upper row is shown together with its corresponding complementary in the same column. The election of the reported Talbot planes was due to the fact that such planes showed sharper intensity features. For the sharpest distributions [planes $(18/43)Z_T$ and $(26/43)Z_T$], a power exceeding 60 μW in each spot is measured (corresponding to an optical intensity of about 100 mW/cm^2).

lower variations only a difference in the image contrast can be observed.[13] In the current investigation, according to Eq. (1), this corresponds to a change in V exceeding 3.5 kV. Indeed, increasing the applied voltage from 3.5 to 6 kV just resulted in sharper bright spots. Actually, the lower limit was dictated by the necessity of getting intensity distributions with acceptable contrast, while the upper one was set by the starting of unwanted electric sparks caused by air moisture; in order to overcome this drawback, the PA sample should be located in a specially designed vacuum chamber.

In conclusion, we have demonstrated a MIR TAI consisting of a 3 μm DFG source and a 2D tunable PA. The latter was realized by deposing, through an *ad hoc* adjusted recipe, two facing ITO electrodes on a domain-engineered $LiNbO_3$ crystal. Then, the electro-optic effect can be exploited either to tune or actively control the phase step across the sample. In this way, a variety of intensity patterns has been generated under different distances via the Talbot effect. Such a flexible TAI may extend to the MIR spectral region several applications that are still limited to the visible domain. These range from dynamical spatial light modulators to generation of array of optical wells to be used in microfluidics[18] as well as in manipulation of cold atoms.[19] Finally, realization of patterned ITO electrodes may in future pave the way to the realization of devices capable of manipulating the relative phases of spatially separate parts of a MIR beam as well as of coherent addition of more IR beams.

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