Adaptive Detection of Arbitrarily Shaped Ultrashort Quantum Light States

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(Received 4 May 2012; revised manuscript received 28 June 2012; published 3 August 2012)

A quantum state of light is the excitation of a particular spatiotemporal mode of the electromagnetic field. A precise control of the mode structure is therefore essential for processing, detecting, and using photonic states in novel quantum technologies. Here we demonstrate an adaptive scheme, combining techniques from the fields of ultrafast coherent control and quantum optics, for probing the arbitrary complex spectrotemporal profile of an ultrashort quantum light pulse. The ability to access the modal structure of a quantum light state could boost the capacity of current quantum information protocols.

DOI: 10.1103/PhysRevLett.109.053602 PACS numbers: 42.50.Dv, 03.65.Wj, 42.65.Re

Most of the experiments performed so far in the field of quantum optics have relied on the generation, manipulation, and detection of single photons and other nonclassical light states in single, well-defined modes. Generation of quantum light in a superposition of two spatial or spectrotemporal modes has been used to encode quantum information (e.g., time-bin schemes [1,2]) or for metrological applications [3,4]. However, simple single- or two-mode systems limit capacity in the communication, manipulation, and storage of quantum information and, equally importantly, are not able to seize the complexity of realistic states in the laboratory.

The possibility of using multimode quantum states of light, i.e., a single beam holding several independent quantum channels, may offer many advantages. As much as wavelength multiplexing has revolutionized the area of optical telecommunications, multimode states have the potential to boost the complexity of quantum networks and enhance the execution of quantum information protocols [5,6]. In the spatial domain, the orbital angular momentum of single photons has been explored [7,8], and multimode states have been used in quantum imaging applications [9–11]. In the spectral and temporal domain, they have been proposed for cluster-state quantum computing [12] and for enhanced time metrology [13,14]. The encoding of quantum information in the spectrotemporal degrees of freedom of a single photon has also been proposed for novel quantum cryptographic schemes, such as differential phase shift quantum key distribution [15].

Moreover, the modes where the quantum states are prepared often do not perfectly coincide with those used for their processing and detection, and this may degrade the quality of applications based on such states. For example, future quantum networks require that light not only conveys information through optical links but also interacts with atomic species, allowing one to perform quantum processing and implement memory units [16,17]. These tasks demand a very specific and precise preparation of the photonic wave packet, i.e., of its spatiotemporal mode, such that it optimally couples to the different possible interfaces. This goal has already motivated a series of theoretical proposals [18,19] and experiments with ultrafast [20] and quasi-cw [21,22] single photons and with shaped two-photon wave packets [23].

We have developed an adaptive method to realize the mode-selective detection of quantum light states. Besides demonstrating the capability to detect and characterize states in unknown and arbitrarily shaped modes, we also show that our scheme can be an important tool for novel quantum information protocols based on the encoding of qubits and qudits onto the spatiotemporal degrees of freedom of light. The main idea relies on optimally mapping the mode structure of a general quantum light state onto that of an intense coherent field (the so-called local oscillator, LO). In a typical experiment for the complete tomographic reconstruction of some quantum light state, homodyne detection only works with sufficient efficiency if the mode $\Psi_{\mathrm{LO}}(\omega, \mathbf{k})$ of the reference classical coherent field is perfectly matched to that of the state under examination [24,25]. If little or no prior information on such a mode is at hand, or if the mode itself has been somehow distorted during the propagation from the source to the detector, one may completely miss the target in the detection stage. Here, we use the measured homodyne data to extract the fitness parameter for a genetic algorithm. The shape of the LO mode is first adaptively adjusted to best match the one of the quantum light state [Fig. 1(a)]. Successively, the complex mode of the quantum state is fully characterized by measurements on the optimized local oscillator.

We put this approach to a first stringent experimental test by analyzing the spectrotemporal (ST) mode $\Psi(\omega)$ of ultrashort *single* photons (in a well-defined spatial mode) with a combination of techniques from the fields of ultrafast coherent control and quantum optics. Choosing to

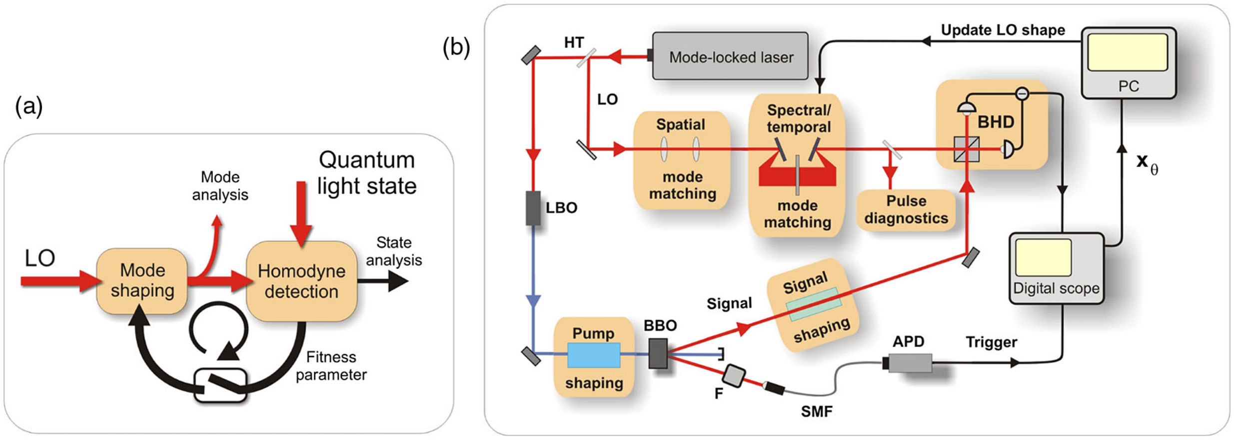

FIG. 1 (color online). (a) Conceptual scheme. A quantum light state is analyzed by a homodyne detector fed with a shaped local oscillator (LO). If the feedback loop is closed, the mode of the LO can be adaptively matched to that of the quantum state, based on measurement results; the latter can thus be fully characterized by measurements on the intense LO field. If the feedback loop is open, the quantum state can be probed in the arbitrarily defined mode of the LO. (b) Experimental setup. Definitions: LBO, lithium triborate crystal; BBO, β-barium borate crystal; APD, avalanche silicon photodiode; F, spectral filter; SMF, single-mode fiber; BHD, balanced homodyne detector; HT, high-transmission beam splitter.

use ultrashort quantum states offers the advantage of an extended bandwidth that allows encoding more information in ST modes, higher rate of information transfer, more precise timing, etc. However, it is important to note that our method is much more general and certainly not confined to ST modes (the full spatiotemporal mode characterization can be simply achieved by also introducing a spatial modulation of the LO [26]) or to the detection of single photons. Different from recent schemes using two-photon interference with a reference coherent field [27], our method can be effectively applied to any quantum state, including bright multiphoton ones, provided a suitable optimization parameter is at hand (e.g., the noise variance in an experiment for the generation of squeezed states). Furthermore, our method is not limited to retrieving the "shape" of quantum light: it directly provides the tools for manipulating and analyzing it. Our scheme is also superior to those involving array detection [28–30], which to our knowledge have never been used to probe any nonclassical state in the ST domain because of high losses and experimental complexity.

We conditionally generate single photons by the process of type-I spontaneous parametric down-conversion [Fig. 1(b)]. The pump field is the second harmonic of a mode-locked 80-fs pulse train at 800 nm. Detection of a tightly filtered idler photon heralds the presence of a highly pure single photon in the signal mode. An ultrafast, time-domain, homodyne detector [31] is used to measure quadrature data. The local oscillator is obtained by splitting a part of the laser emission with a high-transmission beam splitter and is spatially mode-matched to the conditional single-photon mode by a combination of lenses. The ST matching of the LO is performed by means of a spatial light modulator (consisting of two liquid-crystal masks of 2×128 pixels, each 100 μm wide, allowing us to independently apply amplitude and phase spectral modulations by computer-controlled voltage levels) placed in the Fourier plane of a "zero dispersion ($4f$) line" [32]. The spectral and temporal (intensity and phase) profiles of the LO are measured with a spectrometer, an interferometric autocorrelator, and a frequency-resolved optical gate (FROG) device.

In general, the quantum state seen by the homodyne detector in the LO mode is not pure but rather a mixture of single photon and vacuum, whose density matrix can be expressed as

$$\hat{\rho}_{\mathrm{meas}} = \eta|1\rangle_{\Psi_{\mathrm{LO}}}\langle 1| + (1-\eta)|0\rangle_{\Psi_{\mathrm{LO}}}\langle 0|. \quad (1)$$

Apart from systematic and relatively constant factors (such as limited detection efficiency, optical losses, electronic noise, dark counts, and residual spatial mismatch), the ST mode matching between the LO and the single photons has a direct impact on the measured efficiency η, which is then used as the fitness parameter for optimizing the LO ST intensity and phase profiles. The evolutionary genetic algorithm iteratively adjusts the complex LO spectral shape [33,34] until convergence toward a steady optimum value η_{opt} is reached, corresponding to the best possible match between the LO and the photon shape. Since the fitness estimation relies on statistics over many homodyne measurements, a large supply of identical single photons is required for the adaptive procedure to work properly. If the experimental conditions fluctuate too rapidly, convergence is never reached. On the other hand, the system can advantageously adapt to slow changes in the ST profile of the quantum state, so that optimized detection can also be preserved during long acquisitions. Finally, the ST intensity and phase profiles of the optimal LO pulses are fully analyzed, providing a faithful representation of the single-photon mode.

We test the effectiveness of the method with several arbitrarily shaped single-photon pulses. In Fig. 2(a) we show the experimental FROG traces and the reconstructed ST shapes corresponding to single photons that underwent linear dispersion in a 10-cm-long BK7 glass block, resulting in their temporal stretching and spectral chirp. Measuring such dispersed photons with the optimally shaped LO pulses gives $\eta_{opt} \approx 60\%$, whereas using a transform-limited LO pulse would reduce it to less than 50%. If, instead of a short glass block, the photons had propagated through a long optical fiber, the resulting quantum state would have been lost to any detection system not taking these ST distortions into account.

More complex modulations on the profile of the single photon are obtained by shaping the 400 nm pulses pumping the parametric down-conversion crystal. In fact, heralded single photons inherit the spectral properties of the pump if the filtering of the herald idler mode is sufficiently tight [35–37]. Here we place a Michelson interferometer (MI) in the path of the pump pulses to the parametric crystal; the MI splits the pump pulse and recombines the two copies with an adjustable relative delay that causes a sinusoidal modulation of the spectrum. The spectral modulation period is inversely proportional to the delay. We use two different MI configurations, placing either a peak or a valley of the sinusoidal modulation in correspondence to the maximum of the pump spectral profile. In the first case, the MI essentially acts as a spectral filter for the pump. The single photon is also shown to acquire a correspondingly narrower spectrum with a flat spectral phase, translating into a stretched temporal profile with a FWHM duration of about 180 fs [Fig. 2(b)] to be compared to the ≈ 100 fs of an unmodulated single-photon pulse. In the second case, the MI digs a hole in the middle of the pump spectrum, thus producing a two-peaked spectral and temporal

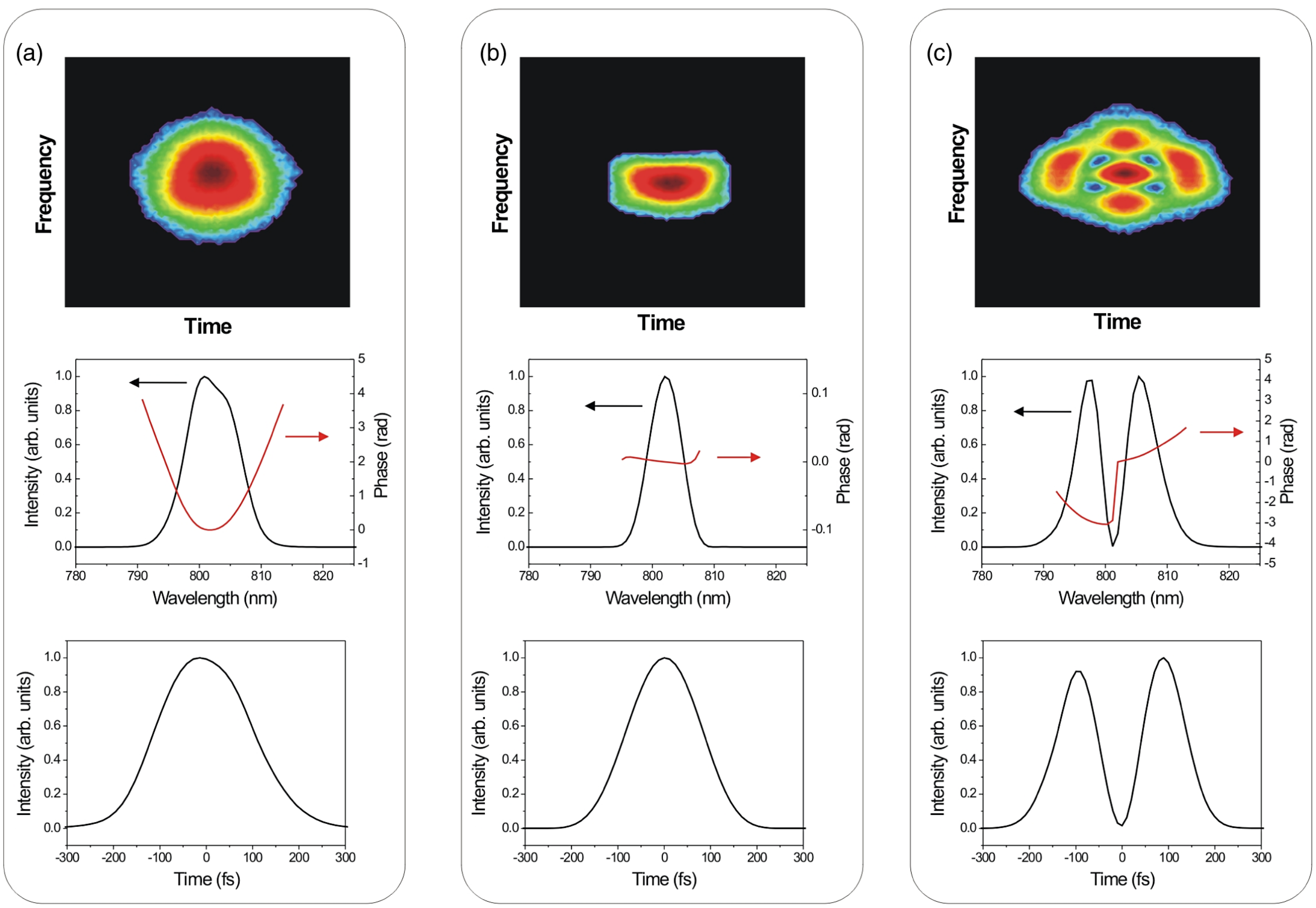

FIG. 2 (color online). Measuring the shape of a single photon. Experimental FROG traces (top panels), reconstructed spectral intensity and phase (middle panels), and temporal intensity profiles (bottom panels) for the optimal LO pulses matching (a) a frequency-dispersed single-photon (FWHM spectral width of about 9.4 nm); (b) a spectrally cropped single-photon (FWHM spectral width of about 6.0 nm); and (c) a spectrally and temporally two-peaked single-photon (note the expected π phase jump in the center of the spectrum). The maximum value of the homodyne efficiency is about 60% for cases (a) and (b), whereas a slight degradation of the pump spatial mode is likely responsible for an efficiency of about 45% in case (c).

configuration that is transferred to the heralded single-photon [Fig. 2(c)].

In the latter case, from both the spectral and temporal points of view, the single photon does not occupy just one peak or the other, but rather exists in a coherent superposition over both peaks. The coherent delocalization in time and frequency thus allows one to define new spectrotemporal modes Ψ_1 and Ψ_2 based on these peaks [see Fig. 3(a)] and use them to encode, manipulate, and detect qubit information with a single photon. For instance, one can assign the state $|1\rangle_{\Psi_1}$ to the photon occupying the first spectral peak and the state $|1\rangle_{\Psi_2}$ to the photon in the second one. Such a pump modulation thus allows the realization of the $(|1\rangle_{\Psi_1}|0\rangle_{\Psi_2} + |0\rangle_{\Psi_1}|1\rangle_{\Psi_2})/\sqrt{2}$ single-photon qubit.

Reversing the perspective used so far, instead of optimizing the LO mode to match the mode of the quantum state, one can also use a properly shaped LO to probe its structure. Setting the LO in the orthogonal spectral mode, obtained by adding a $\phi_{LO} = \pi$ phase shift between the two spectral peaks [Fig. 3(b)], corresponds to performing a homodyne measurement probing the orthogonal state $(|1\rangle_{\Psi_1}|0\rangle_{\Psi_2} - |0\rangle_{\Psi_1}|1\rangle_{\Psi_2})/\sqrt{2}$. As expected, we find a vanishing efficiency in this case [see the reconstructed Wigner function of the corresponding vacuum state in Fig. 3(g)] and, if the relative phase shift ϕ_{LO} is continuously varied, we observe the corresponding cosinusoidal η modulation [Fig. 3(e)], a proof of the coherent nature of the superposition state, in contrast to a statistical mixture.

The above discussion can be readily extended to higher-dimensional spectral qudits, in the current setup, by simply increasing the MI time delay between the two pump pulses. While the generated single photon is still delocalized between just two temporal modes, in the frequency domain it breaks up coherently in a series of equidistant spectral peaks with a comblike structure. These distinct spectral modes correspond to the maxima of the sinusoidal modulation of the pump spectrum. Their number is roughly limited by the ratio of pump to idler-filter bandwidth: the greater the pump bandwidth, the higher the number of independent spectral channels available. Each spectral mode can be individually analyzed by our homodyne detection scheme with an appropriately shaped LO, and mutual coherences can be completely probed by extending the experimental approach described above.

Thus, this versatile scheme allows one to deeply probe the structure of complex quantum states, besides optimizing their detection. The presented experiment paves the road to the analysis of the intrinsic multi-Schmidt-mode character of quantum states naturally generated in parametric down-conversion pumped by short pulses, envisaged to support multimode quantum information processing [38–40]. Finally, it should be noted that homodyne measurements with a shaped LO might not only be used in the detection stage but also in the conditional preparation of multimode quantum states.

Combining advanced coherent-control and quantum optics techniques to measure quantum states of light in unknown modes can allow one to recover "unreadable"

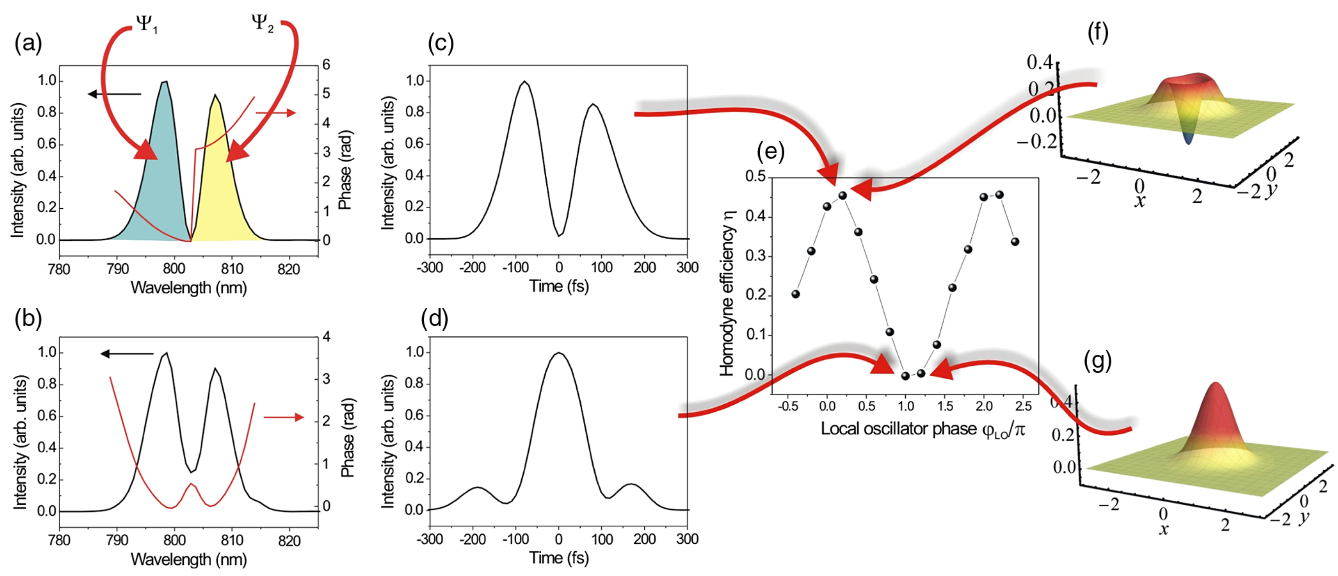

FIG. 3 (color online). Probing a spectrally and temporally delocalized single photon. FROG-measured spectral intensity and phase profiles of the LO mode for (a) $\phi_{LO} = 0$; (b) $\phi_{LO} = \pi$. The corresponding temporal intensity profiles are shown in (c) and (d), respectively. Note the clear double-peak structure of the LO in the $\phi_{LO} = 0$ case and the nearly orthogonal temporal shape obtained in the $\phi_{LO} = \pi$ condition. (e) Variation of the measured single-photon homodyne efficiency η as a function of the phase ϕ_{LO} between the two LO spectral peaks. Reconstructed Wigner functions of the detected state: a single photon in (f) for $\phi_{LO} = 0$ and vacuum in (g) for $\phi_{LO} = \pi$.

quantum features or compensate possible deformations encountered during propagation in arbitrary dispersive or diffractive channels. New exciting opportunities can emerge if quantum states of light are generated and detected in multiple arbitrary modes, as this provides access to a much larger Hilbert space for encoding, manipulating, and decoding quantum information.

M. B. and A. Z. acknowledge the support of Ente Cassa di Risparmio di Firenze, Regione Toscana under Project CTOTUS, EU under ERA-NET CHIST-ERA Project QSCALE, and MIUR, under Contract No. FIRB RBFR10M3SB. K. N. C. acknowledges support from the Alexander von Humboldt Foundation and LaserLab Europe.

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