[0004] The above information disclosed in this Background section is only for enhancement of understanding of the present disclosure, and therefore it may contain information that does not form the prior art that is already known to a person of ordinary skill in the art.

SUMMARY

[0005] Aspects of embodiments of the present disclosure relate to systems and methods for emulating an ising machine and capable of supporting simultaneously high connectivity, multi-body interaction, and a large number of spins.

[0006] According to ~~some embodiments~~an aspect of the present invention, there is provided an optical computation system including: a light source configured to produce a pump beam; an optical modulator configured to receive a modulation mask and to modulate phases or intensities of wavelets of the pump beam based on the modulation mask to generate a modulated beam; a non-linear medium configured to convert a portion of the modulated beam to a second harmonic (SH) beam and to produce an output including the SH beam and an unconverted portion of the pump beam; and a dichroic mirror configured to receive the output of the non-linear medium and to decouple the SH beam and the unconverted portion of the pump beam; a detector configured to detect a first optical power of the unconverted portion of the pump beam and to detect a second optical power of the SH beam; and a controller configured to generate an updated modulation mask based on the first and second optical powers for transmission to the optical modulator.

[0007] In some ~~embodiments~~examples, the optical modulator includes a spatial light modulator that is configured to modulate phases of wavelets of the pump beam to generate the modulated beam.

[0008] In some ~~embodiments~~examples, the modulation mask is a random binary phase pattern.

[0009] In some ~~embodiments~~examples, the spatial light modulator is configured to modulate phases of wavelets of the pump beam by encoding a phase of each one of the

wavelets as either a first phase or a second phase based on the modulation mask, and the first and second phases are 180 degrees apart.

[0010] In some ~~embodiments~~examples, the optical modulator includes a digital micromirror device that is configured to modulate intensities of wavelets of the pump beam to generate the modulated beam.

[0011] In some ~~embodiments~~examples, the optical computation system further includes: a first lens configured to focus the modulated beam inside of the non-linear medium; and a second lens configured to collimate the output of the non-linear medium onto the dichroic mirror.

[0012] In some ~~embodiments~~examples, the detector includes: a first photodetector configured to detect the first optical power of the unconverted portion of the pump beam; and a second photodetector configured to detect the second optical power of the SH beam, and wherein the non-linear medium includes a periodic-poled lithium niobate crystal.

[0013] In some ~~embodiments~~examples, the modulation mask includes a plurality of pixels, and the controller is configured to identify a cluster of the pixels based on the first and second optical powers, and to generate the updated modulation mask by inverting pixels of the cluster of the pixels.

[0014] According to ~~some embodiments~~ another aspect of the present invention, there is provided a method of controlling an optical computation system as described in the aspect above to determine an approximate ground state of a system energy, the method including: driving a light source to generate a pump beam; generating a phase mask; applying the phase mask to a spatial light modulator to modulate phases of wavelets of the pump beam to generate a modulated beam based on the phase mask; and receiving ~~a~~the first ~~optical power of the pump beam~~ and ~~a~~ second optical power~~s of a second harmonic (SH) beam generated based on the pump beam~~ from ~~a~~the detector, wherein the generating the phase mask includes: identifying a cluster of the phase mask; determining a current system energy based on the first and/or second optical powers; determining whether to update the phase mask based at least on the current system energy and a previous minimum system energy; and in

response to ~~determining~~a determination to update the phase mask, updating the phase mask based on the cluster of the phase mask.

[0015] In some ~~embodiments~~examples, the generating the phase mask further includes: in response to determining not to update the phase mask, identifying a lesser of the current system energy and the previous minimum system energy as the approximate ground state.

[0016] In some ~~embodiments~~examples, the generating the phase mask further includes: identifying a thermal energy; calculating a change in system energy based on the current system energy and the previous minimum system energy; and determining a boltzmann probability based on the change in system energy and the thermal energy, and the determining whether to update the phase mask is further based on the boltzmann probability.

[0017] In some ~~embodiments~~examples, the determining whether to update the phase mask includes: determining that a feedback iteration count is less than a threshold; determining to update the phase mask.

[0018] ~~According to some embodiments of the present invention, t~~There is ~~provided~~disclosed an optical computation system including: a light source configured to produce a pump beam; an optical modulator configured to receive a modulation mask and to modulate the pump beam based on the modulation mask to generate a modulated beam; a non-linear medium configured to convert a portion of the modulated beam to a second harmonic (SH) beam and to produce an output including the SH beam and an unconverted portion of the pump beam; and a dichroic mirror configured to receive the output of the non-linear medium and to decouple the SH beam and the unconverted portion of the pump beam; a first camera configured to capture the unconverted portion of the pump beam and to generate a first intensity matrix; a second camera configured to capture the unconverted portion of the pump beam and to generate a second intensity matrix; and a controller configured to generate an updated modulation mask

based on at least one of the first and second intensity matrices for transmission to the optical modulator.

[0019] In some ~~embodiments~~examples, the optical modulator includes a spatial light modulator that is configured to modulate phases of wavelets of the pump beam to generate the modulated beam, and the modulation mask is a binary phase pattern.

[0020] In some ~~embodiments~~examples, the spatial light modulator is configured to modulate phases of wavelets of the pump beam by encoding a phase of each one of the wavelets as either a first phase or a second phase based on the modulation mask, and the first and second phases are 180 degrees apart.

[0021] In some ~~embodiments~~examples, the optical modulator includes a digital micromirror device that is configured to modulate intensities of wavelets of the pump beam to generate the modulated beam.

[0022] In some ~~embodiments~~examples, the controller is configured to generate the updated modulation mask by: determining a camera state as the first intensity matrix, the second intensity matrix, or a weighted sum of the first and second intensity matrices; and determining the updated modulation mask based on the modulation mask and the camera state.

[0023] In some ~~embodiments~~examples, the determining the updated modulation mask based on the modulation mask and the camera state includes: determining the updated modulation mask as a difference between the modulation mask and a multiplication of the camera state and a feedback step size.

[0024] In some ~~embodiments~~examples, the pump beam includes a gaussian pulse of a train of gaussian pulses generated by the light source, and the feedback step size corresponds to a periodicity of the train of gaussian pulses.

[0025] In some ~~embodiments~~examples, the controller is configured to adaptively adjust the feedback step size prior to generating the updated modulation mask.

[0026] According to ~~some embodiments~~ another aspect of the present invention, there is provided an optical computing system including: an optical amplifier configured to generate a

pump beam with a flat phase front; a degenerate optical parametric amplifier configured to generate a signal of double wavelength in small wavelets based on the pump beam; an optical filter configured to filter the pump beam from the signal; an optical beam splitter configured to read out a fraction of the signal; an nonlinear optical crystal configured to generate second-harmonic light based on the signal; a first dual-band reflector configured to separate the signal and the second-harmonic light; an optical receiver configured to couple the second-harmonic light into the optical amplifier; and a second dual-band reflector configured to combine the signal and second-harmonic light into the degenerate optical parametric amplifier.

[0027] In some ~~embodiments~~examples, the optical computing system further includes: a first fourier lens configured to focus the signal into the nonlinear optical crystal for generation of second-harmonic light; and a second fourier lens between the first and second dual-band reflectors and configured to defocus the signal.

[0028] In some ~~embodiments~~examples, each of the first and second dual-band reflectors includes a dichroic mirror or an optical filter.

[0029] In some ~~embodiments~~examples, as the signal continuously traverses the optical computing system, an optical gain of the optical amplifier is increased until optical parametric oscillation occurs.

[0030] In some ~~embodiments~~examples, the optical computing system further includes a first optical modulator between the degenerate optical parametric amplifier and the nonlinear optical crystal and configured to modulate the signal prior to the signal reaching the nonlinear optical crystal to change an effective four-body interaction Hamiltonian of the optical computing system.

[0031] In some ~~embodiments~~examples, the optical computing system further includes a second optical modulator between the nonlinear optical crystal and the optical receiver and configured to modulate the second-harmonic light to change an effective four-body interaction Hamiltonian of the optical computing system.

[0032] According to ~~some embodiments~~ another aspect of the present invention, there is provided an optical computing system including: an optical amplifier configured to generate an amplified signal with a flat phase front; an nonlinear optical device configured to receive the amplified signal and to generate a pump beam through second-harmonic generation based on the amplified signal; a degenerate optical parametric amplifier configured to generate a signal of double wavelength in small wavelets based on the pump beam; an optical filter configured to filter the pump beam from the signal; a first optical beam splitter configured to read out a fraction of the signal; a second optical beam splitter configured to direct a first portion of the signal to an optical modulator for modulation of the portion of the signal and to direct a second portion of the signal to a dichroic mirror; and an optical receiver configured to couple the modulated first portion of the signal into the optical amplifier to generate the amplified signal, wherein the dichroic mirror is configured to combine the second portion of the signal with the pump beam and into the degenerate optical parametric amplifier.

[0033] In some ~~embodiments~~examples, the optical modulator includes a spatial light modulator or a digital micromirror device, and the nonlinear optical device includes a nonlinear optical crystal or an optical waveguide.

BRIEF DESCRIPTION OF THE DRAWINGS

[0034] The accompanying drawings, together with the specification, illustrate example embodiments of the present disclosure, and, together with the description, serve to explain the principles of the present disclosure.

[0035] FIG. 1 illustrates an optical computation system, according to some embodiments of the present disclosure.

WHAT IS CLAIMED IS:

1. An optical computation system comprising:

a light source configured to produce a pump beam;

an optical modulator configured to receive a modulation mask and to modulate the pump beam based on the modulation mask to generate a modulated beam;

a non-linear medium configured to convert a portion of the modulated beam to a second harmonic (SH) beam and to produce an output comprising the SH beam and an unconverted portion of the pump beam; and

a dichroic mirror configured to receive the output of the non-linear medium and to decouple the SH beam and the unconverted portion of the pump beam;

a detector configured to detect a first optical power of the unconverted portion of the pump beam and to detect a second optical power of the SH beam; and

a controller configured to generate an updated modulation mask based on the first and second optical powers for transmission to the optical modulator.

2. The optical computation system of claim 1, wherein the optical modulator comprises a spatial light modulator that is configured to modulate phases of wavelets of the pump beam to generate the modulated beam.

3. The optical computation system of claim 2, wherein the modulation mask is a random binary phase pattern.

4. The optical computation system of claim 2, wherein the spatial light modulator is configured to modulate phases of wavelets of the pump beam by encoding a phase of each one of the wavelets as either a first phase or a second phase based on the modulation mask, and

wherein the first and second phases are 180 degrees apart.

5. The optical computation system of claim 1, wherein the optical modulator comprises a digital micromirror device that is configured to modulate intensities of wavelets of the pump beam to generate the modulated beam.

6. The optical computation system of claim 1, further comprising:

a first lens configured to focus the modulated beam inside of the non-linear medium; and

a second lens configured to collimate the output of the non-linear medium onto the dichroic mirror.

7. The optical computation system of claim 1, wherein the detector comprises:

a first photodetector configured to detect the first optical power of the unconverted portion of the pump beam; and

a second photodetector configured to detect the second optical power of the SH beam, and

wherein the non-linear medium comprises a periodic-poled lithium niobate crystal.

8. The optical computation system of claim 1, wherein the modulation mask comprises a plurality of pixels, and

wherein the controller is configured to identify a cluster of the pixels based on the first and second optical powers, and to generate the updated modulation mask by inverting pixels of the cluster of the pixels.

9. A method of controlling an optical computation system to determine an approximate ground state of a system energy, the method comprising:

driving a light source to generate a pump beam;

generating a phase mask;

applying the phase mask to a spatial light modulator to modulate phases of wavelets of the pump beam to generate a modulated beam based on the phase mask; and

receiving a first optical power of the pump beam and a second optical power of a second harmonic (SH) beam generated based on the pump beam from a detector,

wherein the generating the phase mask comprises:

identifying a cluster of the phase mask;

determining a current system energy based on the first optical powers;

determining whether to update the phase mask based at least on the system energy and a previous minimum system energy; and

in response to determining to update the phase mask,

updating the phase mask based on the cluster of the phase mask.

10. The method of claim 9, wherein the generating the phase mask further comprises:

in response to determining not to update the phase mask,

identifying a lesser of the current system energy and the previous minimum system energy as the approximate ground state.

11. The method of claim 9, wherein the generating the phase mask further comprises:

identifying a thermal energy;

calculating a change in system energy based on the current system energy and the previous minimum system energy; and

determining a boltzmann probability based on the change in system energy and the thermal energy, and

wherein the determining whether to update the phase mask is further based on the boltzmann probability.

12. The method of claim 9, wherein the determining whether to update the phase mask comprises:

determining that a feedback iteration count is less than a threshold;

determining to update the phase mask.

13. An optical computation system comprising:

a light source configured to produce a pump beam;

an optical modulator configured to receive a modulation mask and to modulate the pump beam based on the modulation mask to generate a modulated beam;

a non-linear medium configured to convert a portion of the modulated beam to a second harmonic (SH) beam and to produce an output comprising the SH beam and an unconverted portion of the pump beam; and

a dichroic mirror configured to receive the output of the non-linear medium and to decouple the SH beam and the unconverted portion of the pump beam;

a first camera configured to capture the unconverted portion of the pump beam and to generate a first intensity matrix;

a second camera configured to capture the unconverted portion of the pump beam and to generate a second intensity matrix; and

a controller configured to generate an updated modulation mask based on at least one of the first and second intensity matrices for transmission to the optical modulator.

14. The optical computation system of claim 13, wherein the optical modulator comprises a spatial light modulator that is configured to modulate phases of wavelets of the pump beam to generate the modulated beam, and

wherein the modulation mask is a binary phase pattern.

15. The optical computation system of claim 14, wherein the spatial light modulator is configured to modulate phases of wavelets of the pump beam by encoding a phase of each one of the wavelets as either a first phase or a second phase based on the modulation mask, and

wherein the first and second phases are 180 degrees apart.

16. The optical computation system of claim 13, wherein the optical modulator comprises a digital micromirror device that is configured to modulate intensities of wavelets of the pump beam to generate the modulated beam.

17. The optical computation system of claim 13, wherein the controller is configured to generate the updated modulation mask by:

determining a camera state as the first intensity matrix, the second intensity matrix, or a weighted sum of the first and second intensity matrices; and

determining the updated modulation mask based on the modulation mask and the camera state.

~~18. The optical computation system of claim 17, wherein the determining the updated modulation mask based on the modulation mask and the camera state comprises:~~

~~determining the updated modulation mask as a difference between the modulation mask and a multiplication of the camera state and a feedback step size.~~

~~19. The optical computation system of claim 18, wherein the pump beam comprises a gaussian pulse of a train of gaussian pulses generated by the light source, and~~

~~wherein the feedback step size corresponds to a periodicity of the train of gaussian pulses.~~

~~20. The optical computation system of claim 18, wherein the controller is configured to adaptively adjust the feedback step size prior to generating the updated modulation mask.~~

~~21~~1. An optical computing system, comprising:

an optical amplifier configured to generate a pump beam with a flat phase front;

a degenerate optical parametric amplifier configured to generate a signal of double wavelength in small wavelets based on the pump beam;

an optical filter configured to filter the pump beam from the signal;

an optical beam splitter configured to read out a fraction of the signal;

an non-linear optical crystal configured to generate second-harmonic light based on the signal;

a first dual-band reflector configured to separate the signal and the second-harmonic light;

an optical receiver configured to couple the second-harmonic light into the optical amplifier; and

a second dual-band reflector configured to combine the signal and second-harmonic light into the degenerate optical parametric amplifier.

~~22~~2. The optical computing system ~~in~~of claim ~~21~~1, further comprising:

a first fourier lens configured to focus the signal into the non-linear optical crystal for generation of second-harmonic light; and

a second fourier lens between the first and second dual-band reflectors and configured to defocus the signal.

~~23~~3. The optical computing system ~~in~~of claim ~~21~~1, wherein each of the first and second dual-band reflectors comprises a dichroic mirror or an optical filter.

~~24~~4. The optical computing system ~~in~~of claim ~~21~~1, wherein, as the signal continuously traverses the optical computing system, an optical gain of the optical amplifier is increased until optical parametric oscillation occurs.

~~25~~5. The optical computing system ~~in~~of claim ~~21~~1, further comprising a first optical modulator between the degenerate optical parametric amplifier and the non-linear optical crystal and configured to modulate the signal prior to the signal reaching the non-linear optical crystal to change an effective four-body interaction Hamiltonian of the optical computing system~~.~~; and

~~26. The optical computing system in claim 24, further comprising~~ a second optical modulator between the non-linear optical crystal and the optical receiver and configured to modulate the second-harmonic light to change ~~an~~the effective four-body interaction Hamiltonian of the optical computing system.

~~27~~6. An optical computing system, comprising:

an optical amplifier configured to generate an amplified signal with a flat phase front;

a non-linear optical device configured to receive the amplified signal and to generate a pump beam through second-harmonic generation based on the amplified signal;

a degenerate optical parametric amplifier configured to generate a signal of double wavelength in small wavelets based on the pump beam;

an optical filter configured to filter the pump beam from the signal;

a first optical beam splitter configured to read out a fraction of the signal;

a second optical beam splitter configured to direct a first portion of the signal to an optical modulator for modulation of the portion of the signal and to direct a second portion of the signal to a dichroic mirror; and

an optical receiver configured to couple the modulated first portion of the signal into the optical amplifier to generate the amplified signal,

wherein the dichroic mirror is configured to combine the second portion of the signal with the pump beam into the degenerate optical parametric amplifier.

~~28~~7. The optical ~~computation~~computing system of claim ~~27~~6, wherein the optical modulator comprises a spatial light modulator or a digital micromirror device, and

wherein the non-linear optical device comprises a non-linear optical crystal or an optical waveguide.

8. An optical computation system, comprising:

a light source configured to produce a pump beam;

an optical modulator configured to receive a modulation mask and to modulate phases or intensities of wavelets of the pump beam based on the modulation mask to generate a modulated beam;

a non-linear medium configured to convert a portion of the modulated beam to a second harmonic (SH) beam and to produce an output comprising the SH beam and an unconverted portion of the pump beam;

a dichroic mirror configured to receive the output of the non-linear medium and to decouple the SH beam and the unconverted portion of the pump beam;

a detector configured to detect a first optical power of the unconverted portion of the pump beam and to detect a second optical power of the SH beam; and

a controller configured to generate an updated modulation mask based on the first and second optical powers for transmission to the optical modulator.

9. The optical computation system of claim 8, wherein the optical modulator comprises a spatial light modulator that is configured to modulate phases of wavelets of the pump beam to generate the modulated beam,

wherein the modulation mask is a random binary phase pattern,

wherein the spatial light modulator is configured to modulate phases of wavelets of the pump beam by encoding a phase of each one of the wavelets as either a first phase or a second phase based on the modulation mask, and

wherein the first and second phases are 180 degrees apart.

10. The optical computation system of claim 8, wherein the optical modulator comprises a digital micromirror device that is configured to modulate intensities of wavelets of the pump beam to generate the modulated beam.

11. The optical computation system of claim 8, further comprising:

a first lens configured to focus the modulated beam inside of the non-linear medium; and

a second lens configured to collimate the output of the non-linear medium onto the dichroic mirror.

12. The optical computation system of claim 8, wherein the detector comprises:

a first photodetector configured to detect the first optical power of the unconverted portion of the pump beam; and

a second photodetector configured to detect the second optical power of the SH beam, and

wherein the non-linear medium comprises a periodic-poled lithium niobate crystal.

13. The optical computation system of claim 8, wherein the modulation mask comprises a plurality of pixels, and

wherein the controller is configured to identify a cluster of the pixels based on the first and second optical powers, and to generate the updated modulation mask by inverting pixels of the cluster of the pixels.

14. The optical computation system of claim 8, wherein the detector comprises:

a first camera configured to capture the unconverted portion of the pump beam and to generate a first intensity matrix, and

a second camera configured to capture the unconverted portion of the pump beam and to generate a second intensity matrix; and

wherein the controller is configured to generate an updated modulation mask based on at least one of the first and second intensity matrices by:

determining a camera state as the first intensity matrix, the second intensity matrix, or a weighted sum of the first and second intensity matrices, and

determining the updated modulation mask based on the modulation mask and the camera state for transmission to the optical modulator.

15. A method of controlling the optical computation system of claim 8 to determine an approximate ground state of a system energy, the method comprising the steps of:

driving the light source to generate the pump beam;

generating a phase mask;

applying the phase mask to a spatial light modulator to modulate phases of wavelets of the pump beam to generate a modulated beam based on the phase mask; and

receiving the first and second optical powers from the detector,

wherein the generating step comprises:

identifying a cluster of the phase mask;

determining a current system energy based on the first and/or second optical powers;

determining whether to update the phase mask based at least on the current system energy and a previous minimum system energy; and

in response to a determination to update the phase mask, updating the phase mask based on the cluster of the phase mask.